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Informational efficiency of the European Union emission allowance market

MASTER'S THESIS IN ENVIRONMENTAL ECONOMICS
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Kaarina Toivonen
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Author Kaarina Toivonen		
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Abstract

This thesis studies the informational efficiency of the European Union emission allowance (EUA) market. In an efficient market, the market price is unpredictable and profits above average are impossible in the long run. The main research problem is does the EUA price follow a random walk. The method is an econometric analysis of the price series, which includes an autocorrelation coefficient test and a variance ratio test. The results reveal that the price series is autocorrelated and therefore a nonrandom walk. In order to find out the extent of predictability, the price series is modelled with an autoregressive model. The conclusion is that the EUA price is autocorrelated only to a small degree and that the predictability cannot be used to make extra profits. The EUA market is therefore considered informationally efficient, although the price series does not fulfill the requirements of a random walk. A market review supports the conclusion, but it is clear that the maturing of the market is still in process.

Keywords

Emissions trading, emission allowance market, informational efficiency, random walk

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Tiivistelmä

Tässä Pro gradu -tutkielmassa tarkastellaan Euroopan unionin päästöoikeusmarkkinoiden informaatiotehokkuutta. Informaatiotehokkailla markkinoilla hintaa ei voida ennustaa eikä pitkällä aikavälillä voida saada keskimääräistä suurempaa tuottoa. Tutkimusongelmana on, seuraako päästöoikeuden hinta satunnaiskulkua. Menetelmänä on hintasarjan ekonometrinen analyysi, johon kuuluu autokorrelaatiokerrointesti sekä varianssisuhdetesti. Tulosten mukaan hintasarja on autokorreloitunut, minkä johdosta hintasarja ei voi olla satunnaiskulku. Ennustettavuuden selvittämiseksi hintasarjaa mallinnetaan auto-regressiivisen mallin avulla. Johtopäätös on, että päästöoikeuden hinta on vain vähäisessä määrin autokorreloitunut ja ennustettavuutta on mahdoton hyödyntää tuottojen kasvattamiseksi. Päästöoikeusmarkkinat ovat siis informaatiotehokkaat, vaikka hintasarja ei täytäkään satunnaiskulun vaatimuksia. Markkinakatsaus tukee tätä johtopäätöstä, mutta on selvää että markkinoiden kehittyminen on vielä kesken.

Avainsanat
Päästökauppa, päästöoikeusmarkkinat, informaatiotehokkuus, satunnaiskulku

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Foreword

This thesis is part of the project “Market analysis and risk management of EU emissions trading” (MARMET), which is carried out in cooperation by the University of Helsinki and the Helsinki University of Technology. The aim of the project is to develop a price estimation model of European Union emission allowances (EUAs) and risk management methods for companies participating in the EUA market. The project is mainly funded by the Climbus technology programme, which is supervised by the National Technology Agency, Tekes. Five Finnish companies also contribute to the project.

I wish to express my gratitude to all the researchers and fellow students taking part in the MARMET project. I address my special thanks to the coordinator of the project, Professor of Environmental Economics Markku Ollikainen.

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Kaarina Toivonen

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List of abbreviations

AC	autocorrelation
ADF	augmented Dickey-Fuller
AIC	Akaike information criterion
APP	Asia-Pacific Partnership on Clean Development and Climate
APT	arbitrage pricing theory
APX	Amsterdam Power Exchange
AR	autoregressive
ARCH	autoregressive conditional heteroskedasticity
ARMA	autoregressive moving average
BIC	Bayes information criterion
CAPM	capital asset pricing model
CDM	clean development mechanism
CER	certified emission reduction
CITL	Community Independent Transaction Log
COP	Conference of the Parties
CO_2	carbon dioxide
GARCH	generalized autoregressive conditional heteroskedaticity
GHG	greenhouse gas
EC	European Commission
ECX	European Climate Exchange
EEX	European Energy Exchange
ERU	emission reduction unit
EXAA	Energy Exchange Austria
EUA	European Union emission allowance
ETS	Emissions Trading Scheme
GSN	Green Stream Network Oy
IID	independently and identically distributed
INC	Intergovernmental Negotiating Committee
IPCC	International Panel on Climate Change
JI	joint implementation
MA	moving average
NAP	national allocation plan
OECD	Organization for Economic Co-operation and Development
OTC	over-the-counter
PAC	partial autocorrelation
RW1-3	random walk hypothesis 1-3
UNEP	United Nations Environmental Program
UNFCCC	United Nations Framework Convention on Climate Change
WMO	World Meteorological Organization

List of tables and figures

1 Introduction

The European Union Emissions Trading Scheme (ETS) was established to address the threat of climate change. The increased concentration of greenhouse gases is expected to cause significant changes in temperature, weather conditions, sea level, glaciers, etc. According to research, the Earth's mean surface temperature is predicted to increase during the next 100 years by 1.4-5.8°C, which is a faster warming rate than in 10 000 years (IPCC 2001). With the ratification of the Kyoto Protocol, 37 countries made a binding commitment to emission reductions. The European Union agreed to reduce its emissions by 8% from the 1990 level during 2008-2012. This target was divided among member countries by the burden sharing agreement. The Emissions Trading Scheme is the main instrument of the European Union to reduce greenhouse gas emissions.

The European Union relies on emissions trading because it ensures a predetermined total level of emissions and it also offers flexibility to companies in attaining their obligations, as they can choose whether to reduce emissions or buy emission allowances from other companies (European Commission 2000, 8). The advantage of emissions trading in relation to other instruments is its cost-efficiency; emissions are reduced where it is economically reasonable. The political process of constructing and implementing the scheme's framework was remarkably fast. The emissions trading directive came into force only three years after the Commissions initiative. The intention was to establish the ETS quickly to gain experience of emissions trading before the Kyoto period 2008-2012 and wider international trade.

The ETS came into force on 1 January 2005. It covers about 12 000 installations from energy, iron, steel, mineral and forest sectors, which produce 46% of carbon dioxide emissions in the European Union. The first year and a half of the newfound market have been promising. In 2005, about 322 million European Union emission allowances (EUAs) were traded, the turnover being 14.6%. The average price in 2005 was about 20€, but volatility has been high. The most active market participants are large power companies, banks and investment funds. (Capoor & Ambrosi 2006, 14.) The market has been disturbed by uncertainty regarding future regulation and some technical issues such as problems with allowance registries. Overall, companies and authorities have learned a lot about emissions trading and the maturing of the market is in process.

An essential character of a mature and well functioning market is informational efficiency. Informational efficiency means that market prices reflect all relevant information and that market participants have a good understanding of price formation. In an informationally efficient market, it is impossible to predict future prices and therefore it is also impossible for anyone to constantly beat the market and earn above average returns. Prices react fast to new randomly arriving information and, consequently, the price process itself is random. There is no gradual, predictable adaptation to a new level. (Fama 1970, 383; Malkiel 2003, 59.) The sufficient conditions of informational efficiency are inexistent transaction costs, free information and common agreement on the implications of information (Fama 1970, 387).

In the real world, markets are never perfectly efficient. Therefore, the informational efficiency hypothesis is defined in three different forms (Campbell et al. 1997, 22). According to a relaxed form of the informational efficiency hypothesis, market prices reflect all information contained in historical prices. Consequently, informationally efficient prices should follow a random walk, which is a process where observations are the sum of the preceding observation and a random increment. There econometric requirements for the increments vary depending on the strength of the random walk hypothesis. This thesis focuses on the weakest form, the so-called RW3 model. It allows increments to be dependently distributed, but denies serial autocorrelation. Campbell et al. (1997, 33-55) provide an extensive presentation of the random walk hypothesis and random walk tests, including RW3 tests. The RW3 is most often tested in empirical economic studies.

This thesis studies informational efficiency of the newfound European Union emission allowance market. The issue raises specifically the following questions:

- Is the EUA price reacting fast to new information?
- Do market participants have a clear picture of price formation?

- Is it possible to predict the EUA price?
- Is there a possibility to make extra profits in the EUA market?

The main research problem is if the EUA price process is a random walk. The research method is an econometric analysis. The econometric tests carried out in this study are:

- unit root test
- autocorrelation coefficient analysis
- variance ratio test
- predictability test with an autoregressive model

The unit root test is used to check whether the EUA price process is stationary or has a stochastic trend. The autocorrelation coefficient analysis and variance ratio test reveal if the price series is a random walk. In the case of a random walk, the autocorrelation coefficients are zero and the variance of the series grows linearly with time. The degree of predictability is studied with an autoregressive model. The predictability test was added after the EUA price series proved autocorrelated. In the case of a non-random walk price process, the market may still be regarded as informationally efficient, provided that the price in unpredictable to a sufficient degree.

The analyzed EUA price series is the daily closing price of a futures contract expiring in December 2006, from the European Climate Exchange (ECX). The price is examined during the period 22.4.2005 - 30.3.2006, forming 240 observations. ECX is the most liquid of exchanges providing a platform for about 90% of all trades carried out in exchanges (GSN 2005, 2). The vintage 2006 was chosen because it constitutes the longest time series and it is the most liquid contract in 2006.

The results show that the econometric conditions for a random walk are not completely fulfilled in the EUA case, for there is correlation between the observations. The variance, on the other hand, does grow exactly linearly with time. The autoregressive model was constructed to find out if serial correlation could be used to predict future prices. The results report that the EUA price series is in practice unpredictable, the R-squared being extremely low: about 6,3%. In the light of these results, it can be stated that, from an econometric point of view, the requirements of informational efficiency are not fulfilled. However, from an economic point of view, the European Union emission allowance market is informationally efficient to a great extent because the price process is unpredictable and extra profits seem impossible.

Similar studies on informational efficiency of different markets have been carried out (see Fama (1991, 1577-1581) for a review of studies). The closest reference is the research of Albrecht et al. (2005) on informational efficiency of the United States sulphur dioxide (SO_2) permit market. The findings of Albrecht et al. indicate that although the SO_2 permit price process is not a random walk, it is sufficiently unpredictable, and therefore the SO_2 market seems to be informationally efficient. The SO_2 permit market, concerning the emissions of over 3200 fossil-fuelled electric plants, has served as an example for the development of the ETS (Christiansen et al. 2005, 16).

The structure of this thesis is as follows. In chapter 2, I introduce international climate policy and the European Union Emissions Trading Scheme. In chapter 3, I present the theoretical framework of this study, which includes the portfolio theory, the informational efficiency hypothesis, and the random walk hypothesis. The portfolio theory defines the asset pricing principles that constitute the foundation of informational efficiency theory. Random walk hypothesis, on the other hand, determines the conditions of the price process in informationally efficient markets. The EUA markets and the price data are described in chapter 4. Chapter 5 includes a presentation of the econometric analyses. I discuss the results and conclude in chapter 7.

2 The European Union Emissions Trading Scheme

In this chapter, I introduce international climate policy aiming at combating climate change. I also present the European Union's emissions trading directive, which defines the goals, measures and arrangements of the European Union Emissions Trading Scheme.

2.1 International climate policy

According to latest scientific research, our climate is being severely affected by human activities. The concentrations of greenhouse gases in the atmosphere are rising explosively and they are now higher than they have been in 650 000 years (Siegenthaler et al. 2005). The global mean temperature has increased about 0.6% during the 20th century (IPCC 2001, 4). The latter half of the century has been warmer in the Northern Hemisphere than in 1200 years (Osborn & Briffa 2006). Changes have also appeared in sea level, snow cover, permafrost, glaciers, growing season as well as plant and animal ranges. Extreme weather conditions have become more common. During the next 100 years, the mean temperature is predicted to increase by 1.4-5.8°C, which is a faster warming rate than in 10 000 years. The sea level is expected to rise 0.09-0.88m between years 1990 and 2100. The indirect effects of climate change are increase in diseases, extinction of species, decrease in biodiversity, changes in cereal crops, increase in pests, etc. Socio-economic effects of climate change are difficult to forecast, but they are bound to be serious. Especially poor people in developing countries will be exposed to the threats. (IPCC 2001, 4-12.)

The international community awoke to realise the human impact on our climate by the early 1990's. One of the most important impulses was the publication of the first Intergovernmental Panel on Climate Change (IPCC) scientific report in 1990 (IPCC, 1990a, 1990b, 1990c), which started to reveal the seriousness of climate change. The IPCC had been established two years earlier by United Nations Environmental Program (UNEP) and the World Meteorological Organization (WMO). Since the first report, IPCC has adopted a significant role in presenting the scientific background of climate change, its impacts, and possible measures for adaptation and mitigation. The fourth assessment report will be published in 2007.

The international community responded to the unveiling threat of climate change in 1990 by forming the Intergovernmental Negotiating Committee (INC), which a year later adopted the United Nations Framework Convention on Climate Change (UNFCCC) (INC 1992). The UNFCCC is a treaty signed by 189 countries, aiming to reduce the atmospheric concentrations of greenhouse gases and to prevent dangerous climatic effects of these gases. It came into force in March 1994, and is presently approved by 188 countries. The Convention defines the objectives and principles of the member countries, the Parties. The most essential of these are acting in climate change mitigation, developing new technology, providing carbon sinks, adapting to climate change, and promoting research, information exchange, and education. The Parties form three groups, the so-called Annex I, Annex II and non-Annex I Parties. Annex I Parties include industrialized countries that were members of the Organization for Economic Co-operation and Development (OECD) in 1992 and economies in transition. Annex II Parties are only the OECD members. The Annex II and all other Parties are included in the Non-Annex I Parties. All Parties are obliged to monitor their greenhouse gas emissions and report their actions against climate change. The Annex I countries are required to adopt climate change policies in order to reduce GHG emissions. The OECD members must also assist developing countries in combating climate change by providing financial resources and by promoting technological development. The representatives of all Parties meet annually at a Conference of the Parties (COP), where all decisions regarding the Convention are made. (UNFCCC 2003, 3-6.)

In the COP3 conference in Kyoto in 1997, the Parties adopted the Kyoto Protocol (UNFCCC 1998). The adoptation of the Protocol was great progsress, as it defined concrete, legally binding commitments for industrialized countries to reduce greenhouse gas emissions. The goals may be attained by limiting GHG emissions or by enhancing carbon sinks in forestry and land-use under certain conditions. The Annex I Parties are to cut their emissions by 5% of the base year 1990 during the Kyoto Protocol's first commitment period 2008-2012. The European Union has a common commitment to an 8% reduction of emissions, which is shared by the EU15 member states. The country-specific reduction targets and share of total CO_2 emissions in 1990 are presented in

Table 1. It can be seen that the world's largest emitters are United States with 36.1% of emissions in 1990, the EU 24.2%, Russia 17.4%, Japan 8.5%, Canada 3.3% and Australia 2.1%. The most significant polluters in the EU are Germany, UK, Italy, France and Spain. The tightest reduction commitments are made by Denmark, Germany and Luxembourg. Most countries have a goal of 6-8% reductions. Finland, France, New Zealand, Russia and Ukraine have to stay at the 1990 level, whereas Portugal, Greece, Spain, Ireland, Iceland, Norway and Sweden can increase their emissions. (UNFCCC 2003, 15.)

Table 1. *CO_2 emission reduction targets of the Kyoto Protocol as a percentage of base year 1990 and share of the total by country (UNFCCC 2003, 15).*

Annex I Party	Limit from '90	Share of emissions	Member of the EU	Limit from '90	Share of emissions
Australia*	108%	2.1%	Austria	87%	0.4%
Bulgaria	92%	0.6%	Belgium	92.5%	0.8%
Canada	94%	3.3%	Denmark	79%	0.4%
Croatia	95%	-	Germany	79%	7.4%
Czech Rep.	92%	1.2%	Greece	125%	0.6%
Estonia	92%	0.3%	Finland	100%	0.4%
EU-15	92%	24.2%	France	100%	2.7%
Hungary	94%	0.5%	Ireland	113%	0.2%
Iceland	110%	0.0%	Italy	93.5%	3.1%
Japan	94%	8.5%	Luxembourg	72%	0.1%
Latvia	92%	0.2%	Netherlands	94%	1.2%
Lithuania	92%	0.0%	Portugal	127%	0.3%
New Zealand	100%	0.2%	Spain	115%	1.9%
Norway	101%	0.3%	Sweden	104%	0.4%
Poland	94%	3.0%	UK	87.5%	4.3%
Romania	92%	1.2%			
Russian Fed.	100%	17.4%			
Slovakia	92%	0.4%			
Slovenia	92%	-			
Switzerland	92%	0.3%			
Ukraine	100%	-			
USA*	93%	36.1%			

*Countries did not ratify the Kyoto Protocol

The entry into force of the Kyoto Protocol required that enough Parties to the Convention ratify it. This meant 55 Parties and enough Annex I Parties so that 55% of 1990 CO_2 emissions of all Annex I Parties are encompassed. The requirement turned out to be tough because the big emitters USA and Russia were hesitating. After several years of political debate, the Kyoto Protocol finally entered into force in February 2005 along with Russia's ratification. Russia's decision was reasonable, because its emissions have dropped from the 1990 level by 30% and it can profit of emission trading as a net seller. Russia will also profit from the JI projects. (European Commission 2004). The United States and Australia opted out of the contract. If it were not for the activity of the European Union, the Kyoto Protocol would not have come into force after the change of course of the US (Michaelowa & Butzengeiger 2005, 1).

The Kyoto Protocol includes mechanisms to increase flexibility in the attainment of GHG emission reductions. They were originally proposed by the US and opposed by the EU (Michaelowa & Butzengeiger 2005, 2). The mechanisms are joint implementation (JI), the clean development mechanism (CDM) and international emissions trading. The former two allow industrialized countries to implement projects in economies in transition and developing countries respectively, and thus reduce their greenhouse gas emissions with lower costs. The resulting emission reductions are called emission reduction units (ERU) from JI projects and certified emission reductions (CER) from CDM projects. (UNFCCC 2003, 19-22.)

The future goal in climate policy is to construct a worldwide greenhouse gas market. In addition to the European Union Emissions Trading Scheme, there are already similar but smaller mandatory systems in New South Wales, Oregon and Norway. The Chicago Climate Exchange is a voluntary market place. Canada, Japan, and Switzerland are planning emissions trading projects. (Lecocq & Capoor 2005, 32-35; Nicholls 2005, 20.) The trade of CERs and ERUs already forms an international market. The most active buyers have been Japan, Netherlands and the UK. (Capoor & Ambrosi 2006, 25.)

Since the United States refused to ratify the Kyoto Protocol, international climate policy has been in a confusing situation. The latest political turn is the formation of the Asia-Pacific Partnership on Clean Development and Climate (APP) by the United States, Australia, Japan, India, China and South Korea in January 2006. It is a voluntary framework to address climate, development, energy and environmental issues in particular with technological improvement and transfer. (APP 2006.) Canada is most likely joining the Partnership (Point Carbon 22.5.2006). In addition, the Asian countries

China, India, Indonesia, Korea and Vietnam are still not showing interest in binding emission constraints (Point Carbon 5.5.2006). Upon these grounds, it is difficult to agree on the extension of the Kyoto Protocol, but negotiations are continuing. A working group aiming to prepare negotiations of future climate policy met for the first time in May 2006 in Bonn. Its objective is to form a follow-up for the Kyoto period 2008-2012 without a gap. (UNFCCC 2006b.)

2.2 The European Union Emissions Trading Scheme

The intention of the European Union Emissions Trading Scheme (ETS) is the advancement of greenhouse gas emission reductions and the achievement of member countries' Kyoto targets in the most effective and advantageous way. Emissions trading has been considered as the best instrument because it ensures a predetermined emission cap and offers flexibility and cost savings to companies in attaining their obligations. It also produces an emission price, which companies can take into account in their investments. The European Commission aimed to build the emissions trading system by 2005 to gain experience before the Kyoto period and the beginning of wider international emissions trading in 2008. (European Commission 2000, 8, 10.)

For this reason the ETS was created rapidly. In March 2000, the European Commission published the Green Paper on greenhouse gas emissions trading (European Commission 2000) to invoke discussion about emissions trading. The debate focused on, whether the first period would be mandatory for companies; which sectors would be included; whether the targets would be relative or absolute; and whether the system would be based on a baseline-and-credit or a cap-and-trade approach (Watanabe & Robinson 2005, 12). The competitive effects of emissions trading at national and EU level were also discussed. The goal of harmonized climate policy was challenging due to differing interests of member states and the requirement that the policy should not interfere with competition (Rodi 2005, 193). The framework for the ETS was established after a fast decision process. The emissions trading directive (Directive 2003/87/EC) came into force in October 2003.

The European Union Emissions Trading Scheme is a cap-and-trade system where an overall emission constraint is set and emission allowances are allocated to polluting installations according to historical or projected emissions. The emissions of an installation must equal the amount of allowances in its possession at the end of each year. This objective may be attained by limiting emissions, by trading allowances or both. The abatement and trade decisions are made based on profit maximization and they depend on the marginal abatement costs and the price of allowances. One European Union emission allowance (EUA) corresponds to one tonne of carbon dioxide. The emissions trading directive also concerns other greenhouse gases – methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride – but at this point only CO_2 emissions are regulated. The directive identifies a three-year period 2005-2008 and a five-year Kyoto period 2008-2012. The subsequent periods are projected to last for five years.

The European Union Emissions Trading Scheme covers about 12 000 installations of 6000 companies in all 25 member states. The emissions of these installations total 46% of all CO_2 emissions of the EU. The industries involved in the ETS are power production, iron and steel production and processing, the mineral industry and wood pulp, paper, and card industries. Transportation, chemical, and aluminium sectors were left out due to strong lobbying (Michaelowa & Butzengeiger 2005, 3). The possibility to include aviation has been studied by the aviation working group appointed by the European Commission, but no decisions have yet been made (Aviation working group 2006).

Each member state of the European Union is, according to the directive, obliged to impose a national allocation plan (NAP) that states the total amount of allowances and the allocation of the allowances between different installations for each period. The plan for the first period 2005-2007 was to be submitted to the European Commission by 31 March 2004 and the second plan for the Kyoto period 2008-2012 was due on 30 June 2006. The NAPs should be consistent with national climate policy and national Kyoto targets. Each member country can specify in its climate policy, how the burden of emission reductions is shared between the sectors included in the ETS and excluded from it. If the plan is not in accordance with the criteria, the Commission has the right to reject it. Due to strong industrial lobbying, the allowances are mostly given for free instead of auctioning (Michaelova & Butzengeiger 2005, 1). In the first period 5% of the allowances and in the second period 10% of the allowances may be auctioned. In some regards, auctioning is more advantageous than free allocation, for example it removes the problem of windfall profits (Sijm et al. 2005, 88-92).

The possibility to take advantage of the project-based mechanisms in the ETS was realized with the so-called linking directive (Directive 2004/101/EC) in October 2004. Member countries must declare in their national allocation plans how big a proportion of reductions may be achieved by buying CERs and ERUs. The idea is to ensure sufficient domestic action. The directive does not allow units from nuclear or carbon sink projects. CERs and ERUs have a significant advantage compared to EUAs as they can to be banked to the Kyoto period 2008-2012.

Allowances are allocated to installations every year by 28 February. By 31 March the following year, installations must report to a national authority the previous year's emissions, verified by an authorized verifier. By 30 April, each installation must surrender an amount of allowances equalling its emissions in the previous year to the national authority. If a company does not succeed in returning enough allowances, it has to attain the allowances later and pay a penalty of 40€/tonne of CO_2 in the first period and 100€/tonne of CO_2 in the second. The Commission publishes data concerning verified emissions and surrendered allowances on 15 May. Emission allowances are allowed to be transferred between different years, but not between periods. The surrendered allowances are cancelled by 30 June. (European Commission 2006, 2.) On the grounds of realized emissions, it is possible to draw conclusions about the strictness of the emission cap and companies' abatement costs. Therefore, the publication of emission data may have a great influence on the market.

Table 2 presents country-specific information on allowance allocation and verified emissions in 2005. The table contains the allocation of allowances in 2005-2007, the share of national allocation of the total amount of allowances, number of installations included with an active registry on 30 April 2006, the national allocations for 2005, and verified emissions of 2005. The national registries of Cyprus, Luxembourg, Malta and Poland are not yet active, which prevents all information of being available. The installations of Poland add up to 1166, and the installations of Cyprus, Luxembourg and

Malta to 34 (EU 2005). In addition, the emissions of 279 installations from other countries have not yet been reported (European Commission 2006, 4). The absence of information about emissions from these installations blurs the picture of total emissions.

Table 2. *National allocation plans of EU member states for 2005-2007, share of total allocation, number of installations covered with active registries, allocation for 2005, realized emissions 2005 reported by 4.6.2006, and excess allowances. Data is available only for members with active registries on 4.6.2006. (EU 2005; European Commission 2006,4; CITL 2006.)*

EU member	NAP I (Mt)	Share	Install.	Allocation '05 (Mt)	Emissions '05 (Mt)	Excess (Mt)
Austria	99.0	1.5%	199	32.4	33.4	-1.0
Belgium	188.8	2.9%	309	58.3	55.3	2.9
Czech Rep.	292.8	4.4%	395	95.4	81.2	14.2
Cyprus	17.0	0.3%	-	-	-	-
Denmark	100.5	1.5%	381	37.3	26.5	10.8
Estonia	56.9	0.9%	43	16.7	12.6	4.1
Finland	136.5	2.1%	584	44.6	33.1	11.5
France	469.5	7.1%	1086	150.4	131.3	19.1
Germany	1497.0	22.8%	1846	494.9	473.8	21.0
Greece	223.2	3.4%	140	71.0	71.2	-0.2
Hungary	93.8	1.4%	231	30.1	25.9	4.2
Ireland	67.0	1.0%	109	19.2	22.4	-3.2
Italy	697.5	10.6%	948	213.9	223.1	-9.2
Latvia	13.7	0.2%	93	4.1	2.9	1.2
Lithuania	36.8	0.6%	93	13.5	6.6	6.9
Luxembourg	10.07	0.2%	-	-	-	-
Malta	8.8	0.1%	-	-	-	-
Netherlands	285.9	4.3%	210	86.5	80.4	6.1
Poland	717.3	10.9%	-	-	-	-
Portugal	114.5	1.7%	243	36.9	36.4	0.5
Slovak Rep.	91.5	1.4%	175	30.5	25.2	5.2
Slovenia	26.3	0.4%	98	9.1	8.7	0.4
Spain	523.3	8.0%	816	170.4	181.1	-10.7
Sweden	68.7	1.1%	705	22.2	19.3	2.8
UK	736	11.2%	770	206.0	242.4	-36.4
TOTAL	**6572.4**	**100%**	**9474**	**1843.3**	**1792.8**	**50.5**

The total amount of allocated allowances for the first period 2005-2007 was about 6,6 billion allowances, which makes nearly 2.2 billion allowances per year. The most significant countries with the largest share of total allocation are Germany (22.8%), the UK (11.2%), Poland (10.9%), Italy (10.6%), Spain (8.0%) and France (7.1%). Sector-specifically, the power and heat industry is the biggest sector with 55% of the allowances. Mineral and metal industry hold both about 12%, and oil and gas industries 10% of allowances (Capoor & Ambrosi 2006, 13).

The total allocation for the first ETS period was intentionally generous in order to give companies an opportunity to practice before the Kyoto period 2008-2012. The market was believed to be lacking about 180-270 million allowances during the period (Capoor & Ambrosi 2006, 16). The announcement of realized emissions during 2005 has revealed that the allocation was too generous. The emissions in 2005 of 9474 installations with active registries on 4 June 2006 total 1792.8 Mt CO_2. These installations were allocated 1843.3 M allowances. Hence, the installations have an excess of 50.5 M allowances. One must keep in mind, that this figure does not take account of emissions from all installations. It is estimated that Poland is in excess of 20-30 M allowances (Carbon finance 2006, 2). In addition, countries have decided to divide the total allocation of the three-year period in a way that the allocation of 2005 was "front-loaded" and about 13.8 M larger than the average annual allocation (CITL 2006).

According to Table 2, the allocation of 15 countries exceeded emissions. France and Germany had the most of excess allowances, both about 20 M. Czech Republic, Denmark, and Finland were over 10 M allowances long. Belgium, Estonia, Hungary, Lithuania, Netherlands, Slovak Republic and Sweden were in excess of 2.8 to 6.9 M allowances each. Austria, Greece, Ireland, Italy, Spain and the UK were short of allowances. The most serious shortages were in Italy (9.2 M), Spain (10.7 M), and the UK (36.4 M). For the other countries, the allocation equalled the emissions more or less accurately. It is still possible that the first ETS period as a whole is short, especially if future energy demand and gas prices are high (Capoor & Ambrosi 2006, 17) .

The highest abatement potential in the European Emissions Trading Scheme, if CERs are not taken into account, is in the Central European countries. They are expected to increase their trade significantly, and during the year 2006 at least 30 million allowances are to be supplied from these countries (Point Carbon 23.12.2005, 3). This of course depends on the price level. Of short-term abatement possibilities, the switch from coal to gas is the most reasonable, because power and heating industry emit a large share of emissions and changing the fuel from coal to gas reduces about half of the emissions per unit (Christiansen et al. 2005, 27).

The national allocation plans for the Kyoto period 2008-2012 were to be submitted by the end of June 2006, but several member countries missed the deadline. It remains to be seen, how tight the new restrictions will be. There are signs that suggest more rigid allocations, for example Sweden and Portugal have already decided on a tighter NAP. Germany is expected to reduce allocation significantly. To attain the Kyoto targets and ensure a strong price, the NAPs should be tight. (Point Carbon 9.6.2006.) The NAPs for the first period were badly delayed of the official submission date. The plans of Czech Republic, Greece, Italy and Poland were accepted long after the opening of the ETS. Hopefully, the NAPs for 2008-2012 will not be seriously delayed.

3 Theoretical framework

The theory of informational efficiency determines the concept of an informationally efficient market. In an informationally efficient market, prices reflect all information immediately and price changes are unpredictable. There are no arbitrage opportunities and therefore extra profits are impossible. In addition, market participants have a clear understanding of price formation in an informationally efficient market.

The informational efficiency theory is inseparable from the modern portfolio theory, introduced in the 1950's by Harry Markowitz (1952). The modern portfolio theory and the capital asset pricing model define the principles of asset pricing. The main statement is that the return of an asset should correspond with its systematic risk, which is risk that cannot be diversified away in a portfolio. The efficient market hypothesis is dependent on an underlying asset-pricing model, because without one, the efficiency of asset pricing cannot be assessed.

In a perfectly informationally efficient market, the unpredictable price process follows a random walk, in which the current value is the previous value plus a random increment. The econometric requirements of a random walk are determined by the random walk hypothesis. The random walk tests are a widely used method to empirically study the informational efficiency of financial markets. Even if some predictability exists, a market may still be considered efficient if the predictability cannot be used to constantly make revenue above average.

This chapter presents the modern portfolio theory, the efficient markets hypothesis and the random walk hypothesis. The European Union emission allowance market will later, in chapter 5, be studied against this theoretical framework.

3.1 The modern portfolio theory

Security risk and portfolio risk

The total risk of an asset can be divided into systematic risk, also called market risk, and unsystematic risk, which is also called unique risk. Systematic risk is risk that correlates with the market portfolio and is affected e.g. by inflation, exchange rates and interest rates. Unsystematic risk is independent of market fluctuations. It is affected by the companies' individual characteristics. Unsystematic risk can be eliminated by portfolio diversification, because the variances due to companies' individual characteristics offset each other. The standard deviation of the portfolio returns is reduced as the number of assets in the portfolio increases. After the diversification only the systematic risk present in the market is left. Because the unsystematic risk can be eliminated, only the systematic risk should affect asset pricing. (Knüpfer & Puttonen 2004, 121-123; Brealey et al. 2006, 160-161; Fabozzi et al. 2002, 241-251.)

The systematic risk of an asset or a portfolio is often expressed with the variable beta, β. It describes the sensitivity of an asset to market fluctuations – in other words, how well it correlates with the market return. The beta of a stock, *i*, is:

$$\beta_i = \frac{\sigma_{im}}{\sigma_m^2}, \qquad [3.1]$$

where σ_{im} is the covariance between a stock's return and the market return and σ_m^2 the variance of the market return (Brealey et al. 2006, 167-170). The systematic risk of a portfolio, the portfolio beta, β_p, is:

$$\beta_p = \sum_{i=1}^{N} X_i \beta_i, \qquad [3.2]$$

where the portfolio beta is the average of individual betas weighted by the proportion of each security, X_i. The systematic risk can constitute the total risk of a portfolio, if the unsystematic risk has been eliminated.

The security return can be divided into two components in a same way as the risk. The systematic return correlated with the market return and the unsystematic return, which is independent of market fluctuations. The systematic return can be again expressed as beta and the unsystematic as ε'. Now the security return, *R*, can be noted as:

$$R = \beta R_m + \varepsilon'. \qquad [3.3]$$

The unsystematic return in a diversified portfolio is on average zero. Thus, the ε' can be expressed as the sum of α, which is the average value of unsystematic returns over time, and ε, which is the residual returns. The different components are presented in Figure 1, which pictures security returns (dots) as a function of market returns for single securities. The β expresses the slope of the security returns. It shows how a change in market returns affects the security returns. The term α is the average of the returns and ε is the actual residual returns. The equation 3.3 can be reformed to the form of the so-called market model:

$$R = \alpha + \beta R_m + \varepsilon \qquad [3.4]$$

(Fabozzi et al. 2002, 248-249.)

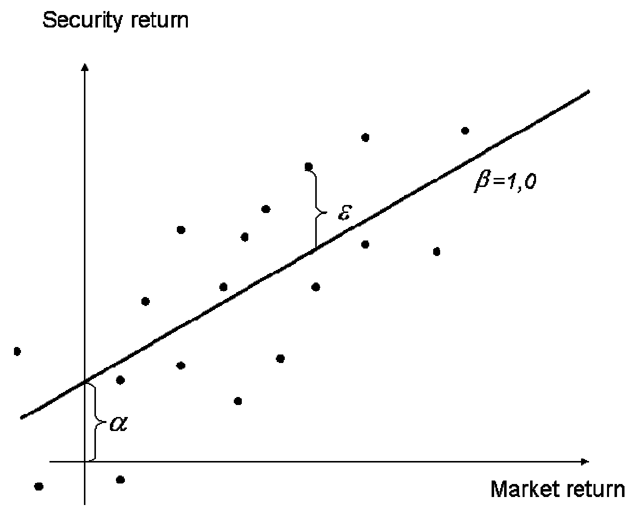


Figure 1. *Model of security returns (Fabozzi et al. 2002, 249).*

Each individual security offers a different combination of expected return and risk. These combinations are presented in Figure 2 as diamonds. The securities down and to the left offer a moderate expected return at a small risk, measured as standard deviation of return. The security A, on the other hand, offers a great expected return, but the risks related to it are significant. By combining these securities, it is possible to obtain any point in the marked area, i.e. any combination of risk and return in this area. Of course, investors seek to maximize expected return and minimize risks, thus the points on the line at the top of the marked area are the best. Among all the possible sets of securities, there are portfolios that provide the highest return for each level of risk. These portfolios are called efficient portfolios and they form the efficient frontier. In Figure 2 they are assets A, B, C, and D. It depends on the investor's preferences, which one of the portfolios on the line he or she chooses. (Brealey et al. 2006, 185-186.)

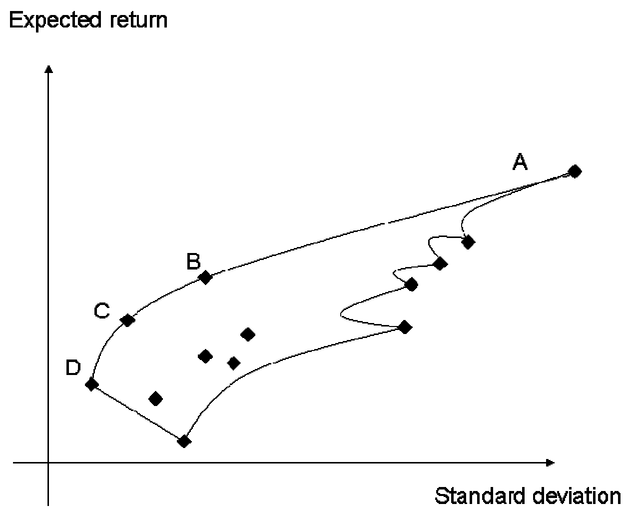


Figure 2. *Efficient portfolios (Brealey et al. 2006, 186).*

Capital asset pricing model

The capital asset pricing model (CAPM), developed by William Sharpe (1964), is founded on the simple principle that securities with higher systematic risk should have higher expected returns and that returns should correlate with the level of systematic risk. The model defines the law of one price, which demonstrates that assets with the same level of risk should have identical expected returns. The underlying assumptions of the CAPM are strong: 1) investors are risk-averse, 2) the time-horizon is the same for all investors, 3) investors have the same expectations abut the future security risks and returns, and 4) the capital markets are perfect. (Fabozzi et al. 2002, 251-253.)

The capital asset pricing model represents the expected return of a composite portfolio of two portfolios: a riskless portfolio, *f*, and a risky portfolio with the same risk as the market portfolio, *m*. The beta is zero for the riskless portfolio and 1 for the risky portfolio. The portfolio beta, β_p, is a weighted average of these. Thus β_p expresses the proportion of investment invested in the risky portfolio and 1- β_p the proportion invested in the riskless portfolio. The expected return, $E(R_p)$, of the composite portfolio is a weighted average of the returns of the portfolios *f* and *m*: R_f and R_m.

$$E(R_p) = (1-\beta_p)\cdot R_f + \beta_p \cdot E(R_m), \qquad [3.5]$$

which can be rewritten as:

$$E(R_p) = R_f + \beta_p \big(E(R_m) - R_f\big).$$

This equation is the CAPM. The interpretation is that an investor should be compensated for giving up consumption possibilities for a period of time and for being exposed to risk. The relationship between the expected return and risk should be linear. Thus, expected return of a portfolio should exceed the riskless rate of return in proportion to the portfolio beta. (Fabozzi et al. 2002, 251-252.)

The CAPM can be also expressed in terms of risk premiums. The risk premium is the expected rate of return minus the riskless rate of return. $E(r_p)$ is the expected portfolio risk premium and $E(r_m)$ is the market risk premium. (Fabozzi et al. 2002, 251-253.) The CAPM states that the expected risk premium is equivalent to the quantity of risk and the market price of risk:

$$E(r_p) = \beta_p E(r_m). \qquad [3.6]$$

(Fabozzi et al. 2002, 252-253.)

The weakness of the CAPM is in its simplicity. The CAPM takes account of the price risk, but ignores many other essential risks. Extended models have been developed to overcome this problem. The multifactor CAPM includes a wider range of risks; the risk due to e.g. future labour income, future investment opportunities and future relative prices of consumer goods (Fabozzi et al. 2002, 255-256.) The arbitrage pricing theory (APT) model recognizes also other factors that affect the rate of return on a security in addition to the market index of the CAPM. The assumptions of the APT model are weaker than of the CAPM. (Fabozzi et al. 2002, 256-258.)

3.2 Informational efficiency

In an informationally efficient market, security prices "fully reflect all available information" (Fama 1990, 1575). The efficient market hypothesis (EMH) states that security prices contain all available and relevant information, that is all information, expectations, and known risks. The price changes in an efficient market are random and unpredictable due to randomly arriving new information. As tomorrow's news is not yet at hand and the information available today is already included in prices, it is impossible to predict tomorrow's prices. It is therefore also impossible to make continuously extra profits that are above average in the market. If these opportunities occurred, they would quickly be eliminated by arbitrage. (Albrecht et al. 2005, 3.)

In an efficient market, the prices need to respond fast to new information so that the information becomes immediately included. If the adjustment happens in steps, the price gives a false signal to the market participants until it reaches the correct level. The market participants in an efficient market have a good conception of price formation and of the market-clearing price. (Albrecht et al. 2005, 2; Fama 1970, 383.)

The law of iterated expectations states the unpredictability of future stock prices (Campbell et al. 1997, 23). The law concerns the expectations of a random variable, *X*, conditional on the information sets I_t and J_t, which are respectively $E[X|I_t]$ and $E[X|J_t]$. The set J_t is superior because it contains also the information of I_t. According to the law:

$$E[X|I_t] = E[E[X|J_t]\,|I_t] \qquad [3.7]$$

The law implies that if only the information I_t is available, "the best forecast one can make of a random variable *X* is the forecast of the forecast one would make of *X* if one had superior information J_t" (Campbell et al 1997, 23). In other words, the limited information set I_t cannot be used to predict the forecast error one would make if the information J_t were at hand. This interpretation emerges from the more accessible form of the law of iterated expectations:

$$E\left[X - E\left[X \middle| J_t\right] \middle| I_t\right] = 0 \qquad [3.8]$$

The law of iterated expectations is useful in stock market analysis. It proves that the expected price change in stock markets is zero and that the best forecast of the next period price is the price today. Mathematically the expected price change is:

$$E_t\left[p_{t+1} - p_t\right] = E_t\left[E_{t+1}\left[V^*\right] - E_t\left[V^*\right]\right] = 0, \qquad [3.9]$$

where E_t expresses the expectations at time t, p_t the security price at time t, and V^* a "fundamental" value of the security price conditional on information I_t at time t. (Campbell et al. 1997, 23-24.)

The efficient market hypothesis has very strict assumptions in its extreme form. The hypothesis assumes that information is costless to all market participants and trading costs are non-existent. In addition, all market participants agree on the implications of current information for the current price. The assumptions are not very plausible, because information and transaction costs exist in all real markets. Therefore, market efficiency must be evaluated after the transaction and information costs are accounted for. It should be noted, that these factors are only potential sources of market inefficiency and do not necessarily mean inefficiency if they occur in a market. (Fama 1970, 387.)

Since the real markets are not perfectly efficient, three levels of efficiency have been defined, based on the information that is reflected in prices. These forms are the strong, semistrong, and weak form, presented in Table 3. In the strong form, the prices reflect all possible information that can be obtained. This means that all market participants from professional investors and corporate managers to private investors are in the same position concerning information. The differences in revenues are determined only by random events. The semistrong form implies that prices reflect all public information, for example announcements of earnings, stock issuing, etc. In the last case, the weak form of market efficiency, prices are determined by all information contained in historical prices. Thus, the requirement is that future prices cannot be predicted and it is impossible to continuously earn extra revenue. (Brealey et al. 2006, 337.)

Table 3. *Three forms of informational efficiency (based on Fama 1970, 383, 388; Brealey et al. 2006, 337).*

Form	**Definition**	**Research problem**
Strong form	Prices reflect all information known to anyone.	Do some people have monopolistic access to information?
Semistrong form	Prices reflect publicly available information.	How quickly do prices respond to public announcements?
Weak form	Prices reflect information contained in historical prices.	Are future returns predictable? To what extent?

Table 3 presents also the research problems associated to the three forms of market efficiency. The strong form can be tested by examining, if some market participants, e.g. professional investment managers, have private information to benefit from. The semistrong form is tested with the so-called event tests, which study the speed of adjustment of prices to new information. The weak form is tested by analysing the predictability of future returns. The tests are based on forecast power of historical time series, dividend yields, earnings and term-structure variables. The random walk tests, carried out in this thesis, are concluded in the weak form tests. The research of short time predictability has been dominant, but recent studies examine also long-term returns. Fama (1991) presents these tests and the main studies and results.

Testing market efficiency is complex. What causes the most ambiguity is that efficiency can only be tested jointly with an equilibrium model, such as the capital asset pricing model, which defines the meaning of proper asset-pricing. This joint hypothesis problem implies that the test results rely ultimately on the asset-pricing model. In fact, market efficiency can never be totally rejected, because the joint model cannot be proven correct. Even if test results indicate inefficiency, it may be impossible to find out if the price behaviour is really due to market inefficiency or is it just that the equilibrium model is inaccurate. (Campbell 1997, 24-25; Fama 1991, 1576.)

In addition to the joint hypothesis problem, it is problematic that the conditions of market efficiency are practically never completely satisfied. Considering these facts, it may be more relevant to measure efficiency than to test its existence. The relative market efficiency in comparison to other markets can also be a fruitful research subject. (Campbell 1997, 24-25.) Fama (1991, 1576) argues that efficient market literature should not be judged on how precise results it produces, but on how it improves our knowledge of stock price behaviour.

During the past decades, the research of market efficiency has revealed many strange things about the markets, which are inconsistent with the efficient market hypothesis. Some of them can be explained by people's irrational behaviour. For example, people have the tendency to irrational attitudes towards risk and false estimates of probabilities (Brealey et al 2006, 344-345). The discipline of behavioural finance has sprung to study these psychological aspects of market functioning. Malkiel (2003, 61) states, that markets sometimes make mistakes in pricing due to psychological factors, but in the long run "true value wins" and the anomalies disappear.

3.3 Random walk hypothesis

A random walk is a stochastic process, in which each value is the sum of the previous value and a random increment. The best forecast of tomorrow's value of a variable is therefore its value today, since the random changes cannot be predicted. The conditional expectation of increments is zero, given the lags of the series. Thus, the historical values of a random walk time series are of no help in forecasting the future values. In the case of price series, the error term can be interpreted as the effect of today's new information on today's price. (Stock & Watson 2003, 458.)

A random walk is a nonstationary process, in other words, a stochastic trend. This results from the fact that the variance of a random walk increases over time and thus the distribution of the variable changes as time passes. The variance and conditional mean of the series are both linear in time. The random walk may have a drift, if it has a tendency to increase or decrease. In this case, the change of the variable is the stochastic change plus a drift parameter. One should not be mistaken to interpret drift as predictability. (Stock & Watson 2003, 446; Campbell et al. 1997, 33.)

Campbell et al. (1997, 31-55) define three versions of the random walk hypothesis, the RW1, RW2, and RW3 models, and present methods to test them. The models differ in the assumptions about the distribution of the increments. The RW1 is the strongest form and its increments are assumed to be independently and identically distributed[1] (IID) with a mean 0 and variance σ^2. The RW1 is expressed as:

$$p_t = \mu + p_{t-1} + \varepsilon_t \qquad \varepsilon_t \sim IID(0, \sigma^2) \tag{3.10}$$

where p_{t-1} is the lagged value of p_t, μ is the possible expected price change or drift and ε_t expresses the increments at time *t*. If the natural logarithm of the price series is used, the increments can be assumed to be normally distributed. As attractive as the RW1 is in its simplicity, it is a theoretical construct and not a realistic model for a long-term asset price analysis. The probability distribution of stock returns cannot be stable for long periods, e.g. for decades. The RW1 can still be tested with various tests of IID, including the Cowles-Jones ratio and runs tests.

The RW2 includes more general processes than the strict RW1. The increments of RW2 are assumed independently but not identically distributed. The model allows for example unconditional heteroskedasticity in the increments, and therefore time-varying volatility. The unpredictability of increments still holds. Testing of independent but unidentical distribution is difficult. The main tests of RW2 hypothesis are filter rules and technical analysis.

In the case of the most general form of random walk, RW3, both assumptions of RW1 are relaxed. The increments are no longer independently and identically distributed. They are assumed dependent but uncorrelated. The model allows for example correlation of squared increments. The RW3 includes the RW1 and RW2 as special cases. The criteria of the three models are presented in Table 4.

[1] Independently distributed implies that the value of a variable provides no information of the value of another variable. Identically distributed means that the variable has the same distribution.

Table 4. *Random walk models and criteria (based on Campbell et al. 1997, 31-33).*

Model	**Increments are:**
RW1	independently and identically distributed
RW2	independently but not identically distributed
RW3	dependent but uncorrelated

The RW3 is the most often empirically tested hypothesis of random walk. The variety of RW3 tests include analysis of autocorrelation coefficients, Portmanteau tests, and the variance ratio test. The autocorrelation coefficients of the first difference series reveal serial correlation of the increments. Portmanteau statistics analyses the sum of squared autocorrelations. The Ljung-Box Q-statistic is a widely used test statistic, which detects nonzero autocorrelation. The variance ratio test is based on the fact that the variance of the random walk increments must be a linear function of time. In chapter 5, the European Union emission allowance price series is tested for fulfilling the criteria of a random walk RW3 with these three methods. The methods are described in more detail then.

4 Market review and price data description

In this chapter, I present the European Union emission allowance (EUA) market and the price data used in the analysis in chapter 5. The market review includes a description of market characteristics, namely the price development, volatility, volumes, trading platforms, products and market participants. Informational efficiency of the EUA market is assessed through these characteristics. It is important to keep in mind the special features of the EUA market. The EUA market is an artificially formed environmental market intended to reduce greenhouse gas emissions. The emission allowances are traded like any commodities, but the market conditions are defined by a regulatory framework. In particular, the national allocation plans and the links to the project-based mechanisms are crucial factors. The main market fundamentals are CO_2 production and the supply of credits from CDM projects. CO_2 production depends especially on weather conditions, fuel prices, and economic growth. (Christiansen et al. 2005, 20-28.)

4.1 The European Union emission allowance market

Price development

Figure 3 presents the price development of European Union emission allowances (EUA) from the broker Spectron from 25 May 2004 to 26 May 2006. Broker data is chosen instead of exchange data, because brokers offer a longer range of price data. The data gives an accurate picture of the general price evolvement, although there are some minor differences among the EUA prices of different brokers and exchanges. Data from earlier dates is not available. The product in question is a forward[2] of December 2005 until its expiration date and since then the vintage 2006.

[2] A forward contract is a legal agreement a to buy or sell an asset at a certain moment in the future for an agreed price called the delivery price, the exercise price or the forward price. Forwards are traded on the over-the-counter market. They usually do not have secondary markets, as standardized futures contracts do.

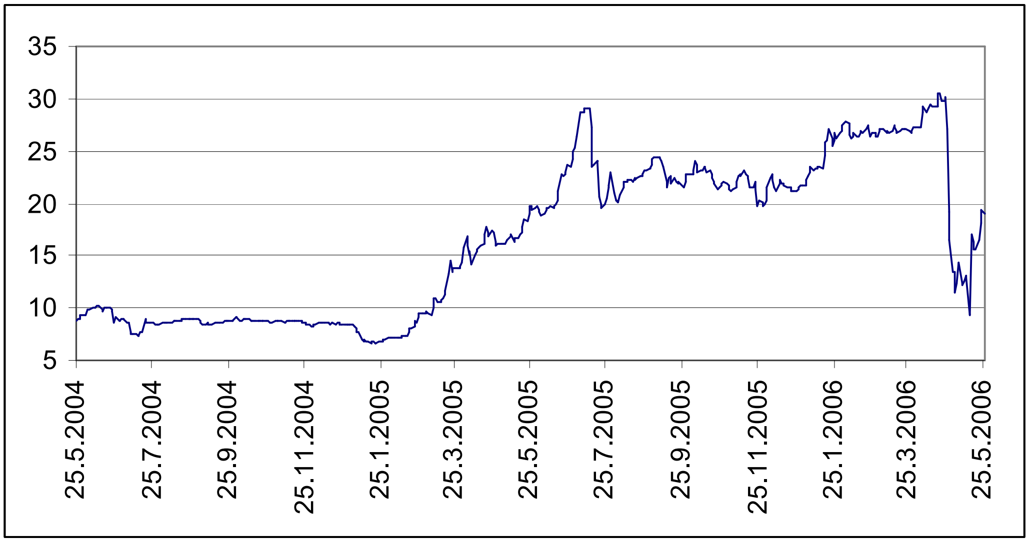


Figure 3. *Price development of Spectron EUA forward 25.5.2004 - 26.5.2006 (source: Reuters 2006).*

The first emission allowances were traded in spring 2003. During the year 2003 the price increased from 6€ to 12€, but came down to about 7-8€ by May 2004 (Lecocq 2004, 32). As can be seen from Figure 3, the price was fixed for several months to about 7-9€ until the beginning of year 2005. After a small bend down, the price began its climb until it reached nearly 30€ in July 2005. This price development surprised most experts and market participants. According to Sijm et al. (2005, 19) the increase was largely due to political decisions on unpredictably strict national allocation plans, but the market reaction was to some extent exaggerated. Behind the price increase there were also high fuel prices, cold weather and the absence of suppliers in the market and uncertainty about the political environment (Lecocq & Capoor 2005, 33.) The price fell suddenly down at the end of June because of weaker UK gas price and the entrance of Czech Republic into the market (Point Carbon 22.7.2005, 2). The price fluctuated around 21-23€ for the rest of the year.

At the beginning of year 2006 the price increased to way above 25 euros in consequence of cold weather and high fuel prices. For a couple of months the price stabilized, and then it reached the record of over 30€ in April driven by fuel prices. The publication of carbon dioxide emission data of year 2005 at the end of April dropped the EUA price below half of its former value. During 24 April -3 May 2005, the price dropped from about 30.20€ to 11.45€. The Netherlands, Czech Republic, France and Spain reported that their emissions had been significantly below the 2005 allocations (Point Carbon 28.4.2006, 2). Altogether, the EU member countries, excluding Poland, were about 50.5 million tonnes in excess of emission allowances for 2005 (CITL 2006). After the drop, the EUA price has started to appreciate again. The reason for this is that some market participants are hedging against power price movements and some companies are not yet selling their surplus allowances. (Point Carbon 26.5.2006, 5-6.)

To define how fast and accurate price changes have been, the price data should be examined thoroughly with event studies. For example, the effect of the publication of emission data is difficult to analyze at one glance because there was no single announcment. The data was to be published all at once on 15 May, but the data leaked into the market prematurely. The Netherlands and Czech Republic published their emission data on 24 April, Spain and France on 26 April. The rest was accidentally published on the Commission's website on 12 May. (Carbon finance 2006, 1-2.)

Exaggerations have also occurred. Especially in the beginning of 2005, market sentiments had an effect on the price. The markets overreacted to announcements concerning national allocation plans (Sijm et al. 2005, 19). Many traders see that the market exaggerated also the influence of year 2005 emissions and the price fell too low, especially as the surplus traders were not selling very eagerly (Point Carbon 28.4.2005, 6).

Volatility

Volatility measures price fluctuations over a certain time period. It can be interpreted as price risk associated to a commodity. Mathematically, volatility is the standard deviation of logarithmic price returns, presented per year (see Appendix I). Figure 4 presents the annualized 30-day rolling volatilities of the Spectron EUA forward price from 25 May 2004 to 26 May 2006. The rolling volatility is calculated daily from prices of 30 previous days. It shows the development and fluctuations of volatility. It can be seen that both extreme and reasonable volatility have occurred. The summer months of 2004 saw high price fluctuations, but the autumn season was more stable. The spring and summer time in 2005 witnessed volatility of over 60% and even 80%, with a more stable short period in June. During the autumn, volatility has fluctuated about between 20-45%. The turn of the year saw the volatility rising to over 40%, but then it started to decrease. In March 2006, volatility went under 20% for the first time after the beginning of ETS, only to bounce to huge figures as prices fell in April. The record-breaking 30-day volatility is over 250%.

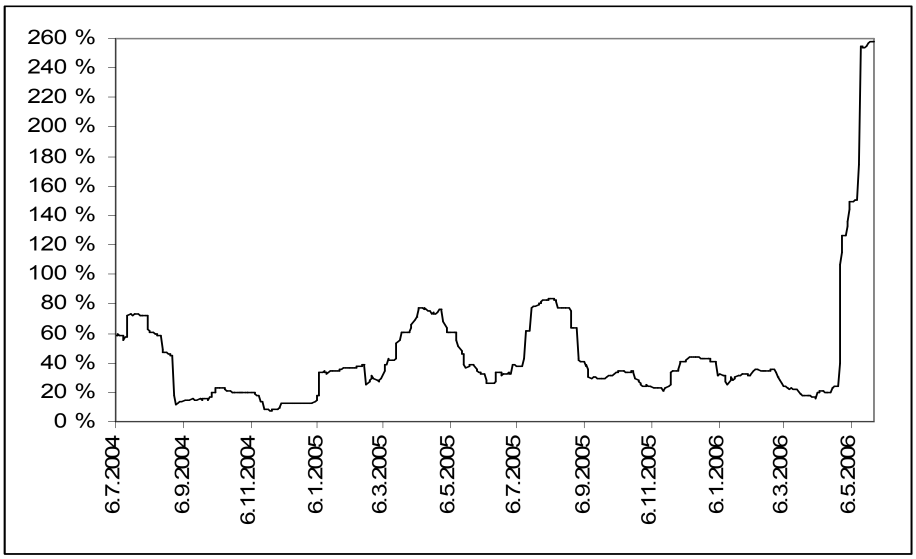


Figure 4. *30-day annualized rolling volatility of Spectron EUA price. Time range 25.5.2004 -26.5.2006.*

Volatility of the EUA market has been high, due to regulatory and technical issues as well as fundamentals. Volatility shows if expected returns vary through time, but it is difficult to tell if the variation is rational (Fama 1991, 1586). Therefore, volatility cannot be used to make conclusions about a market's informational efficiency, although it may indirectly be linked to it.

Volume

Before the EU ETS officially entered into operation, some companies were already preparing for it by trading forward contracts. In 2003 about 30 trades took place, totalling 650 000 tonnes of CO_2. In the following year 2004, volume increased up to about 9 million allowances. The year 2005 saw 322 million allowances traded, the turnover of allowances being 14,6%. The total value of the EUA market was US$8.2 billion. During the first three months of 2006, 203 million allowances were traded. The total value of the market during these three months was US$6.6 billion. (Lecocq & Capoor 2005, 32; Capoor & Ambrosi 2006, 13-14.)

The weekly volume of the over-the-counter (OTC) market and exchanges are presented in Figure 5. It can be seen that volume has been increasing quite steadily since spring 2005. The turn of the year saw volume grow, but at the end of April 2006, the volumes exploded. The reason is partly in high volatility that occurred at the time. The Figure 5 also shows that brokers handle a large part of trade, about 60-80% of all transactions, but the role of exchanges is also growing. In addition to brokers and exchanges, emission allowances are also traded bilaterally between companies. These trades are not taken into account in Figure 5.

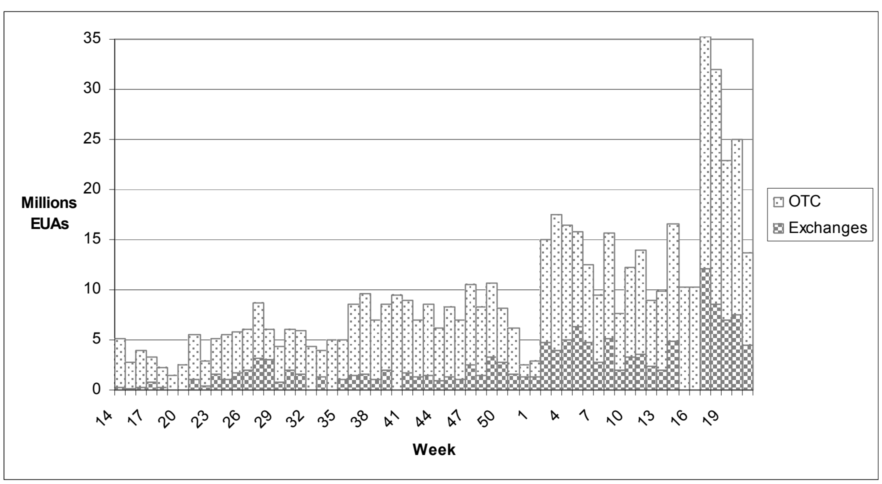


Figure 5. *Weekly volumes in the OTC market and exchanges during weeks from 14/2005 to 14/2006. (No data available of the distribution of trade between brokers and exchanges for the weeks 32/05, 34/05, 40/05, 15/06, and 16/06. Volumes for weeks 15/06 and 16/06 were reported as one number, but are here divided in two.) (Point Carbon April 8 2005 – May 28 2006.)*

Several factors have restricted volume. First, 25% of allowances were not in registries in 2005, in other words, they could not be traded. The possibility to transfer allowances to and from the following year has also decreased volume. Perhaps the most important reason is that many companies have decided to postpone trading, because they have wanted to wait and see how the market evolves or they do not have required knowledge of emissions trading. Uncertainty and the unfamiliar regulation have indeed affected market participants' behaviour. (Capoor & Ambrosi 2006, 14-18). According to an enquiry (Laurikka & Ruokonen 2006, 7), many companies state that trade has been restricted by the immaturity of the market, the high volatility and the unknown effect of trading to the second phase national allocation plans.

The growth of volume refers to market development. Market liquidity is important from the point of view of informational efficiency. The more liquid the market, the more there are ready buyers and sellers, and the less single trades affect the market price. Liquidity eases transactions and makes fast adaptation to new information possible. The exchange-traded futures contracts have more active secondary markets than broker-traded forwards. Therefore, the growth of exchanges is positive in regard of informational efficiency.

Trading platforms, products and market participants

There are eight exchanges in the EUA market. These are European Climate Exchange (ECX), Nord Pool, Powernext, European Energy Exchange (EEX), Energy Exchange Austria (EXAA), Climex Alliance, Komodnita Burza Bratislava (KBB). The Climex Alliance is a union of the local exchanges New Values, SendeCO2, Amsterdam Power Exchange (APX), the APX Power UK, STX Energy Services, and euets.com. Table 5 presents the exchanges along with their opening dates and products. The Nord Pool and ECX offer futures contracts[3], whereas the others offer spot trade[4]. Nord Pool was the first one in the markets in February 2005, EEX followed in March and ECX in April.

[3] A futures contract is is a promise to buy or sell a security at the maturity of the contract at an agreed price, the futures price. Futures are standardized, traded on exchanges and marked-to-market daily.
[4] Spot trade is cash trade for immediate delivery

Climex Alliance, Powernext and EXAA entered into operation at the end of June. The ECX is definetly the most liquid exchange, providing a platform for about 90% of all trades in exchanges (GSN 2005, 2). It also provides the largest variety of futures products. The ECX is planning to list EUA options[5] in the autumn 2006 (Carbon finance 2006, 1). The second biggest exchange is Nord Pool with a 5 % share of trades (GSN 2005, 2).

Table 5. *EUA market exchanges, their launching dates, and products.*

Exchange	**Date of launch**	**Products**
Nord Pool	11.2.2005	Futures, maturity: Dec 2005-2007
EEX	9.3.2005	Spot
ECX	22.4.2005	Futures, maturities: Mar/Jun/Sep/Dec 2005-2007 Mar/Dec 2008 Dec 2009-2012
Climex Alliance	22.6.2005	Spot
Powernext	24.6.2005	Spot
EXAA	28.6.2005	Spot
KBB	27.12.2005	Spot

Before the opening of the ETS, only forward contracts intermediated by brokers could be bought and sold. In February 2005, Nord Pool started to offer standardized futures contracts. EEX was the first to offer spot trade a month later. The forward trade is still dominating as brokers trade about 60-80% of all EUAs. Of exchange-traded contracts, futures constitute 95% and spot trade 5%. This can be concluded from the fact that ECX and Nord Pool offer only futures trade and the other exchanges only spot trading.

The traders in exchanges are large companies, brokers, banks and investment funds. The role of speculants is significant; they trade about 50-60% of all transactions (Ruokonen 2006). Smaller companies have access to exchanges with the intermediation of brokers,

[5] An option is an agreement that gives the holder the possibility to sell (put option) or buy (call option) an underlying asset the expiration date at the so-called strike price. The price of an option is the option price or the option premium.

banks and investment funds. The most active market participants have been power companies. The reason is that they were allocated a large share of allowances and they also already had expertise in trading (Capoor & Ambrosi 2006, 14). At first, the participation of installations from the EU10 countries was restricted by nonfunctionning registries and hesitation, but since then they have entered the markets more actively.

The growing number of trade products and market participants contribute to informational efficiency. A large variety of products assures that traders can realize their plans as they wish and hedge against the future or speculate. A large number of market participants increases liquidity. The fact that there are eight exchanges is on the other hand positive, but causes that the market is decentralized. It is predicted that all the exchanges cannot survive.

4.2 Price data

This chapter introduces the European Union emission allowance (EUA) price data, which is analysed in the following chapter 5. The data consists of daily closing prices of a futures contract on EUAs expiring on 19 December 2006 from the European Carbon Exchange (ECX). The EUA price data, named as series P_t, is presented in Figure 6. The data includes closing prices of trading days during 22 April 2005 - 30 March 2006, altogether 240 observations. The 22 April 2005 is the date when ECX started to offer EUA futures contracts. All price data is provided by Reuters (2006). The price development was described in the previous chapter 4.1.

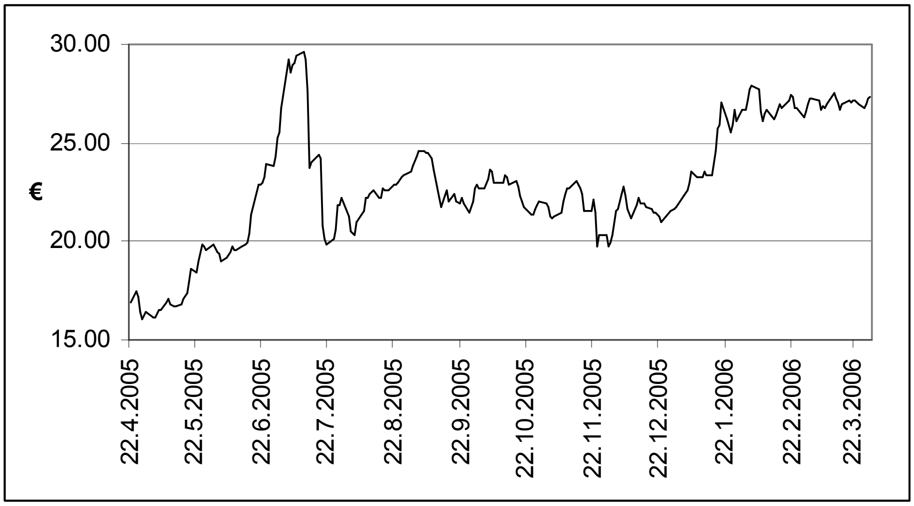


Figure 6. *Price series P_t. Closing price during 22 April 2005 - 30 March 2006 of EUA futures contract of vintage 2006, from the ECX exchange. (Source: Reuters 2006.)*

The ECX futures contract for December 2006 is chosen because it is currently the most liquid product and it offers continuous data until this date. The vintage 2005 was more liquid until the end of 2005, but a long and continuing time series was considered more important than the liquidity rate. Volumes of futures expiring in December 2005 and 2006 are presented in Figure 7.

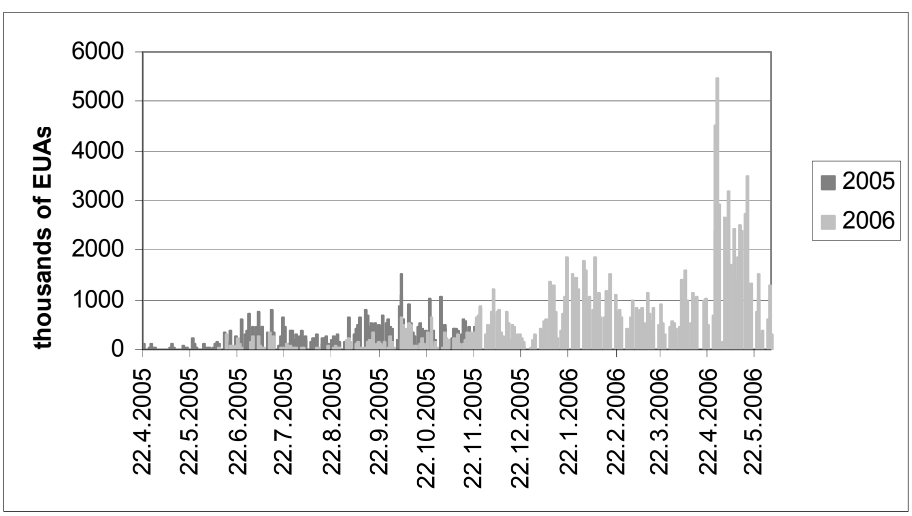


Figure 7. *Volumes of ECX futures contract trades expiring in December 2005 and 2006 in thousands of EUAs. (For vintage 2005 data is available until 23.11.2005.) (Source: Reuters 2006.)*

In the econometric analysis of this thesis, the EUA price will be studied as a natural logarithm series, p_t, and a differentiated natural logarithm series, Δp_t, instead of the original series, P_t. The natural logarithm is used, because the differentiated natural logarithm series expresses changes in the logarithmic series as proportional changes in the original series[6] (Stock & Watson 2003, 209, 432). The natural logarithm of the EUA price is denoted as $p_t = \ln(P_t)$. The difference of the natural logarithm series is denoted as $\Delta p_t = p_t - p_{t-1}$. The Δp_t series can also be interpreted as logarithmic price returns. The differentiation transforms the series into a stationary series, i.e. a series of which the probability distribution does not change over time (Stock & Watson 2003, 447). Stationarity is required in the autocorrelation coefficient analysis and in forming the autoregressive model. The two modifications of the original series, p_t and Δp_t, are presented in Figures 8 and 9. The natural logarithm series has the same appearance as the original series. The differentiated natural logarithm series behaves as a stationary series.

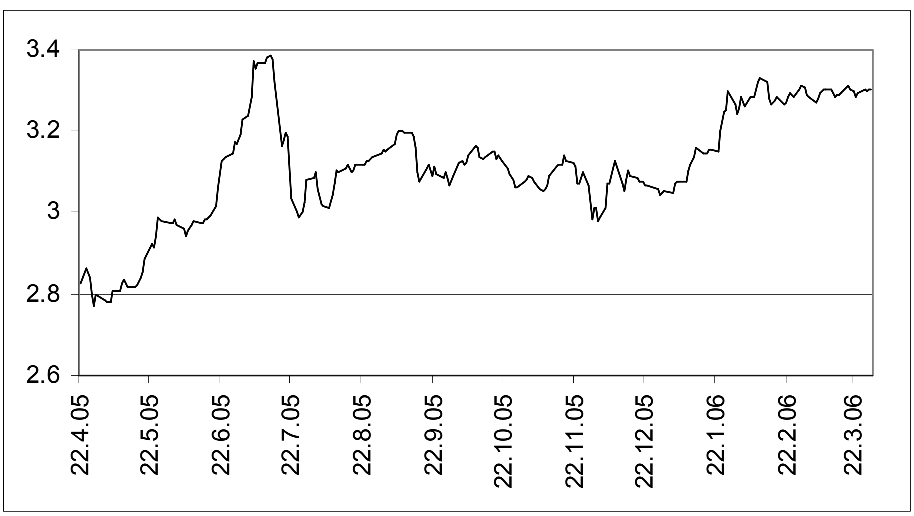


Figure 8. *Natural logarithm price series, p_t.*

[6] $\ln(P_t + \Delta P_t) - \ln(P_t) \cong \frac{\Delta P_t}{P_t}$, when $\frac{\Delta P_t}{P_t}$ is small (Stock & Watson 2003, 209).

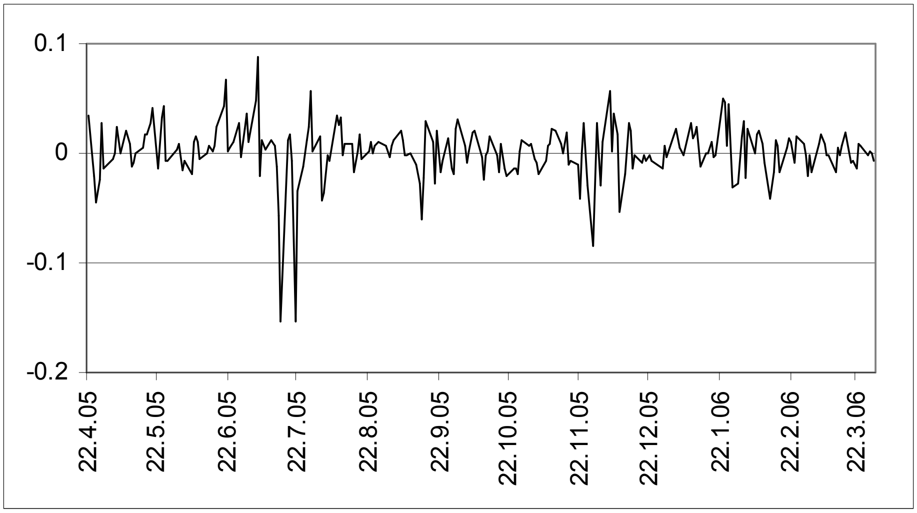


Figure 9. *Differentiated natural logarithm prices series,* Δp_t .

Table 6. *Descriptive statistics of series* P_t, p_t, *and* Δp_t.

Descriptive statistics	P_t	p_t	Δp_t
Mean	22.90	3.12	0.00
Standard Error	0.20	0.01	0.00
Standard deviation	3.10	0.14	0.03
Sample variance	9.62	0.02	0.00
Kurtosis	-0.42	-0.10	11.30
Skewness	-0.04	-0.39	-1.82
Minimum	16.00	2.77	-0.15
Maximum	29.60	3.39	0.09
No. of observations	240	240	239

The descriptive statistics of the three series are presented in Table 6. The original price series, P_t, ranges from 16 to 29.60€, with a mean of 22.9€, variance of 9.62€ and standard deviation of 3.10€. The series is symmetric but platykurtic[7] because its kurtosis is less than 3. The natural logarithm series, $p_{t,}$ is only a transformation of the original series and its values have no practical interpretation. It is also platycurtic and nearly symmetric. The values range from 2.77 to 3.39, with a mean of 3.12 and standard

[7] A variable is platykurtic if it's kurtosis is less than 3 and it's probability density function is "flat".

deviation of 0.14. The differentiated logarithmic prices range from -0.15 to 0.09, with zero mean and standard deviation of 0.03. This means that changes in the original price have ranged from -15% to 9%, the average change being 0%. The series is negatively skewed and strongly leptocurtic[8] (kurtosis 11.30).

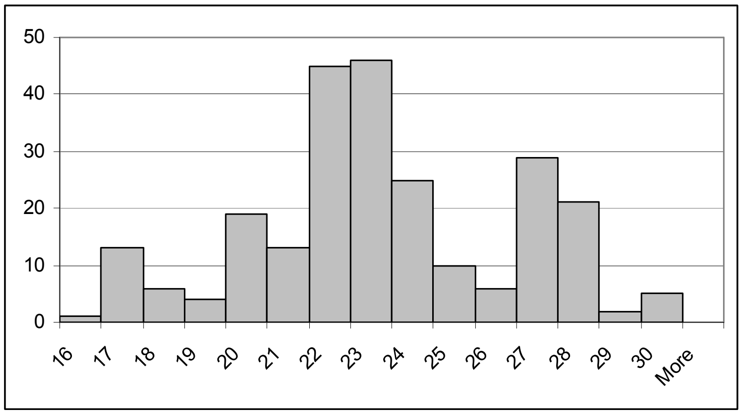


Figure 10. *Histogram of price series P_t.*

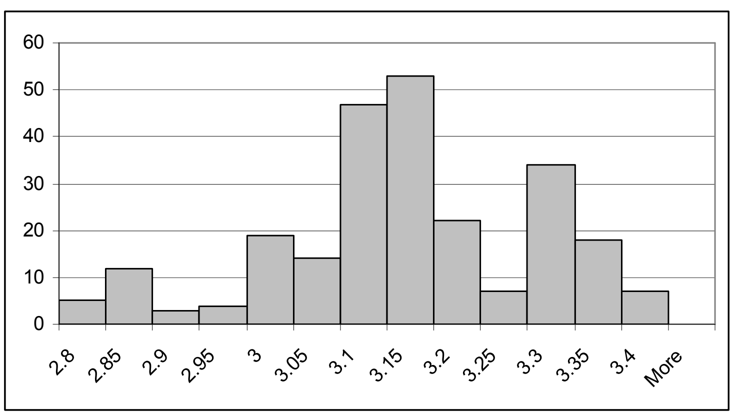


Figure 11. *Histogram of natural logarithm price series p_t .*

[8] A variable is leptokurtic if it's kurtosis is more than 3 and it's probability density function is "peaked".

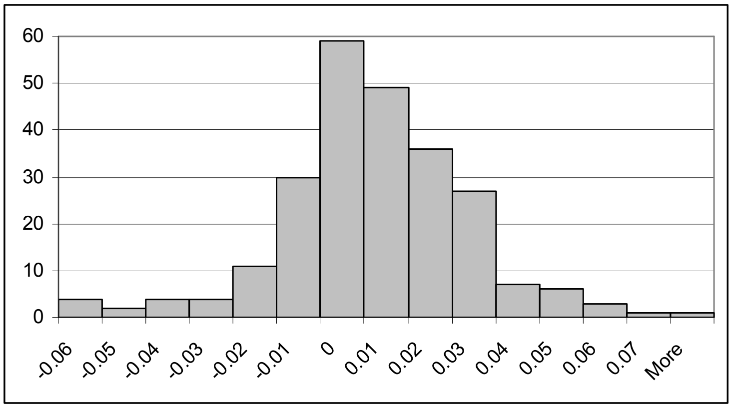


Figure 12. *Histogram of differentiated natural logarithm price series* Δp_t .

Figures 10, 11, and 12 present histograms of the three series. Series P_t has several peaks: a dominating peak at about 23€ and smaller peaks at 28€, 20€, and 17€. The natural logarithm series, p_t, is similar in shape. The distribution of series Δp_t is smoother with only one peak at zero. The series has “fat tails”, which means that it is leptocurtic. The fat tail effect might be a sign of volatility clustering. The negative skewness of the series is obvious.

5 Analysis of informational efficiency

This chapter provides an analysis of informational efficiency of the European Union emission allowance (EUA) market. The analysis includes a unit root test, an autocorrelation coefficient analysis, a variance ratio test, and a test of price predictability. The unit root test is a preliminary test of stationarity. The autocorrelation coefficients and the variance ratio are actual random walk tests, which test the RW3 random walk hypothesis presented in chapter 3.3. The predictability test is added to find out if revealed autocorrelation can be used in price prediction. The analysis is carried out with the natural logarithm and the differentiated natural logarithm of the EUA price, series p_t and Δp_t.

5.1 Unit root test

A unit root test reveals whether a time series that is being analysed is stationary or has a stochastic trend. As was mentioned in chapter 3.3, a random walk has a stochastic trend, but more precisely, it is a first difference stationary process. Therefore, if the EUA price were a random walk, it should have a stochastic trend and the first difference should be stationary.

The null and alternative hypotheses of the unit root test are:

$$H_0 : p_t = \mu + p_{t-1} + \varepsilon_t \qquad [5.1]$$

$$H_1 : p_t - \mu t = \phi\left(p_{t-1} - \mu(t-1)\right) + \varepsilon_t \ , \ \phi \in (-1,1) \qquad [5.2]$$

The term μ denotes drift and term ε_t expresses a zero-mean stationary process, to which applies that each increment added to the partial sum of increments has a significant effect on the partial sum's variance, σ_0^2, in other words, the variance increases at approximately the same rate as time T:

$$0 < \sigma_0^2 = \lim_{T\to\infty}\left[\frac{1}{T}\left(\sum_{t=1}^{T}\varepsilon_t\right)^2\right] < \infty \qquad [5.3]$$

The term ϕ is a coefficient of which the value is tested. If the null hypothesis is accepted, the series has a stochastic trend and a unit root. In this case, a shock to p_t will appear in the expectations of all future values and the shock is said to be permanent. On the other hand, the rejection of the null hypothesis and approval of the alternative indicates that the series is stationary and does not have a unit root. In this case, a shock in p_t is temporary and its effect decreases as the number of lags grows. (Campbell et al. 1997, 64-65.)

However, the acceptance of the null hypothesis is not sufficient proof of a random walk, because the null hypothesis contains also nonrandom walk alternatives. In the null hypothesis the increments might be predictable[9], which is not allowed in a random walk. (Campbell et al. 1997, 65.) The unit root test is nonetheless a useful tool in analysing a time series.

The unit root test used here is the Augmented Dickey Fuller (ADF)[10] test. The tested series are the natural logarithm and the difference of the natural logarithm of the original price. The results of these tests are presented in Table 7. The right number of lags is determined with Akaike information criteria (AIC) (see Appendix II for details of information criteria). The test requires that the error terms are independent and homoskedastic, so a sufficient number of lags must be included. This is why Akaike information criteria is more preferable than Bayes criteria (BIC), although both information criteria have the tendency to select small lag values (Stock & Watson 2003, 487-488).

[9] The increments are allowed to be a zero-mean stationary process (Campbell et al. 1997, 65).

[10] ADF uses the regressor $p_{t=}\alpha + \mu t + \phi p_{t-1} + \sum_{i=1}^{k}\beta_i \Delta p_{t-i} + \varepsilon_t$, where α and μ are both drift terms, *k* the number of lags

Table 7. *ADF unit root test results for series p_t and Δp_t.*

Variable	ADF test statistic	Significance level	Null hypothesis	Lags
p_t	0.9142	over 10%	not rejected (P=0.8186)	5
Δp_t	-8.2125	under 1%	rejected (P< 0.0019)	2

The ADF test statistic is 0.9142 for the natural logarithm series and -8.2125 for the differentiated natural logarithm series. In the case of the p_t series, the null hypothesis is accepted at 82% probability. In the case of the difference of the natural logarithm, the null hypothesis is rejected at over 99% probability. Thus, the p_t series quite likely does contain a unit root and has a stochastic trend. It is clear that the Δp_t series is stationary. As a conclusion, it seems that the EUA series is a first difference stationary process, which implies that it might be a random walk.

5.2 Random walk tests

In this chapter, the EUA price series is tested against the criteria of RW3, the most general form of random walk hypotheses. The random walk tests include studies of autocorrelation and partial autocorrelation coefficients and variance ratios. According to the RW3 hypothesis, the autocorrelation coefficients of the first difference series should be zero and variance should grow linearly with time (Campbell et al. 1997, 44, 48). The tests reveal, whether this is true or not in the case of the EUA price. The autocorrelation coefficients and partial autocorrelation coefficients are studied for both the natural logarithm and the difference of the natural logarithm of the EUA series. The variance ratio test is carried out with the differentiated natural logarithm series.

Autocorrelation coefficients

Autocorrelation (AC) of a series Y at lag k expresses correlation between lags Y_t and Y_{t-k}. The k^{th} autocorrelation coefficient is:

$$\rho_k = \frac{\operatorname{cov}(Y_t - Y_{t-k})}{\sqrt{\operatorname{var}(Y_t)\operatorname{var}(Y_{t-k})}}. \qquad [5.4]$$

The k^{th} autocorrelation coefficient can be estimated as:

$$\rho_k = \frac{\sum_{t=k+1}^{T}(Y_t - \bar{Y})(Y_{t-k} - \bar{Y})}{\sum_{t=1}^{T}(Y_t - \bar{Y})^2}, \qquad [5.5]$$

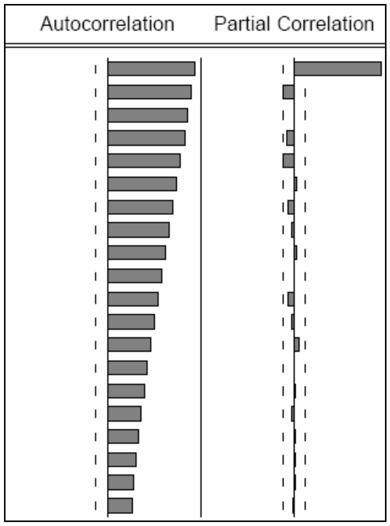
where $\bar{Y}$ is the sample mean of Y and T is the number of observations. (Stock & Watson 2003, 435; Eviews 5 user's guide 2004, 314-315.) If the k^{th} coefficient is nonzero, there is k^{th} order serial correlation. Serial autocorrelation can be captured by an autoregressive (AR) model, which represents Y_t as a linear function of its lagged values. The regressors of a p^{th} order autoregressive model are Y_{t-1}, Y_{t-2} …, Y_{t-p}. If the values of the autocorrelation coefficients die out geometrically as k increases, the series follows a low-order autoregressive process. If the values drop soon to zero as k increases, the series follows a low-order moving-average (MA) process, in which Y_t is modelled with recent values of white noise error terms. (Stock & Watson 2003, 441; Eviews 5 user's guide 2004, 314-315; Hamilton 1994, 48.)

Partial autocorrelation (PAC) at lag k expresses correlation of the values of series Y at k periods apart, ignoring the correlation from the intervening lags. The k^{th} partial autocorrelation coefficient is the regression coefficient on Y_{t-k}, when Y_t is regressed on a constant, Y_{t-1}, …, Y_{t-k}. The PAC coefficient, ϕ_k, can be estimated as:

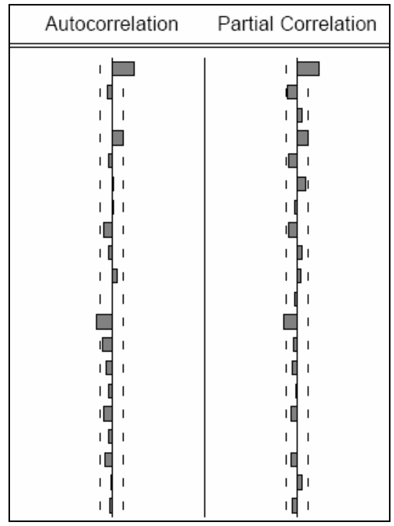
$$
\begin{cases}
\rho_1 & \text{for k=1} \\
\dfrac{\rho_k - \sum_{j=1}^{k-1} \phi_{k-1,j}\rho_{k-j}}{1 - \sum_{j=1}^{k-1} \phi_{k-1,j}\rho_{k-j}} & \text{for k>1}
\end{cases}
\qquad [5.6]
$$

where ρ_k is an estimation of the k^{th} order autocorrelation and $\phi_{k,j} = \phi_{k-1,j} - \phi_k \phi_{k-1,k-j}$. If the series is a pure p^{th} order autoregressive process, the partial autocorrelation coefficients cut off at lag *p*. In the case of a pure moving average process, the partial autocorrelation dies out gradually to zero. (Eviews 5 user's guide 2004, 315-316.)

Figure 13 and Table 8 present autocorrelation coefficients (AC) and partial autocorrelation coefficients (PAC) of the logarithmic series, p_t, and the differentiated logarithmic series, Δp_t. Table 8 shows also the Ljung-Box *Q*-statistic and its p-value. The *Q*-statistic tests the null hypothesis that there is no autocorrelation up to order *k*. It is distributed according to a chi-square distribution with degrees of freedom equal to the number of autocorrelations. (See Appendix III for details.) In Figure 13, the coefficients are shown along with bounds indicating difference from zero at 95% probability (EViews 5 user's guide 2004, 315).



p_t



Δp_t

Figure 13. *Autocorrelation and partial autocorrelation of series p_t and Δp_t with 95% probability bounds.*

Table 8. *Autocorrelation (AC) and partial autocorrelation (PAC) coefficients, and Ljung Box Q-statistics with p-values of series p_t and Δp_t.*

	p_t				Δp_t			
Lag (*k*)	**AC**	**PAC**	***Q***	**p**	**AC**	**PAC**	***Q***	**p**
1	0.97	0.97	233.62	0	0.25	0.25	15.37	0.000
2	0.94	-0.12	451.33	0	-0.05	-0.12	15.88	0.000
3	0.90	0.00	653.84	0	0.01	0.06	15.90	0.001
4	0.86	-0.07	840.32	0	0.13	0.12	20.13	0.000
5	0.82	-0.12	1008.80	0	-0.03	-0.10	20.32	0.001
6	0.78	0.03	1160.90	0	0.03	0.09	20.54	0.002
7	0.73	-0.07	1296.60	0	0.02	-0.03	20.65	0.004
8	0.69	-0.03	1416.50	0	-0.09	-0.11	22.48	0.004
9	0.64	0.03	1522.30	0	-0.03	0.05	22.70	0.007
10	0.60	0.00	1615.60	0	0.07	0.04	24.08	0.007
11	0.56	-0.06	1696.40	0	0.01	-0.02	24.12	0.012
12	0.52	-0.02	1765.80	0	-0.17	-0.14	31.32	0.002
13	0.48	0.06	1825.80	0	-0.10	-0.04	34.06	0.001
14	0.45	-0.01	1877.70	0	-0.05	-0.05	34.74	0.002
15	0.41	0.01	1922.40	0	-0.03	-0.01	35.03	0.002
16	0.38	-0.02	1960.50	0	-0.09	-0.06	37.04	0.002
17	0.35	0.01	1993.20	0	-0.03	0.00	37.26	0.003
18	0.32	0.01	2021.20	0	-0.08	-0.06	38.84	0.003
19	0.30	0.01	2045.30	0	0.00	0.05	38.84	0.005
20	0.28	-0.01	2066.00	0	-0.02	-0.06	38.93	0.007

The series p_t has strong positive autocorrelation. The first order autocorrelation is 0.97. The autocorrelation coefficients decrease gradually as k increases. Partial autocorrelation is significant at a 5% significance level only at the first lag. The Ljung-Box Q-statistic and its p-values indicate that the null hypothesis of no autocorrelation is rejected at all lags. These results are typical for an economic nonstationary level series.

The series Δp_t has positive first order autocorrelation. The series does not include significant (at 5% significance level) autocorrelation at other lags. The first autocorrelation coeffificient is 0.25, which means that the lagged change in the logarithmic price explains the current change. According to the Ljung-Box Q-statistic and its small p-values (0-0.7%), the null hypothesis of no autocorrelation is rejected at all lags. These results imply that the series Δp_t follows an autoregressive (AR1) process, but this remains to be confirmed.

As a conclusion, the series p_t and Δp_t both have significant autocorrelation and do not fulfill the requirements of a random walk. This does not come as a surprise for the level series p_t, but the stationary Δp_t could have been nonautocorrelated. The results raise the question, if the serial correlation can be used to predict future prices. This issue is studied in chapter 5.3.

Variance ratios

According to the random walk hypotheses, the variance of a random walk's increments is a linear function of time. The variance ratio (VR) shows if this requirement holds. The variance ratio is calculated for the difference of the natural logarithm series, Δp_t. In the two period case, the variance of the series today should be twice the variance of the series yesterday, i.e. the variance of $\Delta p_t + \Delta p_{t-1}$ should be twice the variance of Δp_t. To compare the variance of longer intervals, a term q is introduced to express the interval in trading days. Thus, when q is e.x. 6, the weekly development of the variance is examined by comparing the series Δp_t to the series until Δp_{t-5}. Mathematically:

$$VR(q) = \frac{Var[\Delta p_t(q)]}{qVar(\Delta p_t)} = 1 + 2\sum_{k=1}^{q-1}\left(1 - \frac{k}{q}\right)\rho(k), \qquad [5.7]$$

where $\rho(k)$ is the k^{th} order autocorrelation coefficient of Δp_t. The variance ratio should be statistically indistinguishable from one in the case of a random walk. (Campbell et al. 1997, 48-49.)

A standardized test statistic, $\psi(q)$, tests the null hypothesis of RW3, which requires uncorrelated increments of a process. The null hypothesis allows general forms of heteroskedasticity. Under the null hypothesis, the variance ratio approaches one for all q as the number of observations increases. The test statistic is presented in detail in Appedix IV. (Campbell et al. 1997, 53-55.)

Table 9. *Variance ratios, test statistics, and significance levels for series* Δp_t.

q	VR(q)	$\Psi(q)$	Sig.
2	1.2562	4.0100	over 0.0005
3	1.3211	3.3714	over 0.0027
4	1.3623	3.0312	over 0.0027
5	1.4425	3.1611	over 0.0027
6	1.4940	3.1280	over 0.0027
7	1.5425	3.1154	over 0.0027
8	1.5875	3.1087	over 0.0027
9	1.6056	2.9868	0.0028
10	1.6185	2.8673	0.0040
11	1.6461	2.8347	0.0046
12	1.6745	2.8160	0.0048
13	1.6727	2.6844	0.0074
14	1.6562	2.5122	0.0120
15	1.6358	2.3429	0.0192

Table 9 presents the variance ratios (VR(q)), the test statistics ($\psi(q)$), and the significance levels at intervals from 2 to 15 trading days. When q is 2, the variance ratio is about 1.26. As q increases, the variance ratio grows until q=12, after which it starts to decrease. The results are nearly all significant at a 1% significance level. Only when q

gets values 14 and 15, the significance level increases to 2%. The null hypothesis is accepted at all levels of q with at least 98.08% probability, and at q=2 with over 99.95% probability. The results imply that the variance of the differentiated logarithmic EUA price series grows linearly with time just like a random walk should. The previous analysis of serial correlation, on the contrary, provides cogent evidence that the Δp_t series is a nonrandom walk. The revealed autocorrelation prevents the series from fulfilling the econometric requirements of a random walk. The next task is to find out whether the autocorrelation may be used to predict future prices or can the market still be considered informationally efficient.

5.3 Predictability

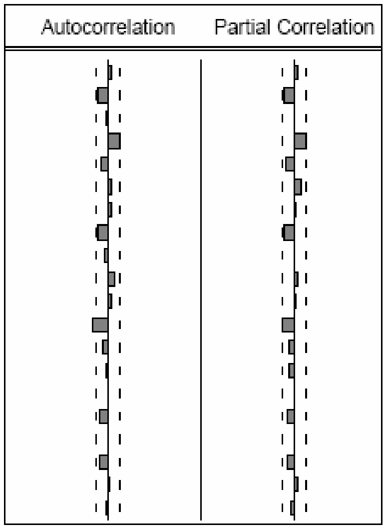
In an informationally efficient market, it is impossible to make extra profits by forecasting from historical price data. The predictability of the EUA markets is judged by the R-squared of the best possible price forecasting model, which captures serial correlation. The model is chosen on the grounds of autocorrelation, partial autocorrelation, significance of coefficients and Bayes information criterion (BIC). The minimized BIC indicates the right number of lags to include to the model (see Appendix II). The studied series is the differentiated logarithmic series, Δp_t, for its stationarity.

The autocorrelation and partial autocorrelation coefficients, presented in chapter 5.2, suggest an autoregressive moving average ARMA(1,1) model, but a more precise study shows that this is not the case. Table 10 presents the relevant properties of the considered AR(1), AR(2), and ARMA(1,1) models. The properties include the Bayes information criterion, R-squared, adjusted R-squared, variable coefficients, and T-statistics. As can be seen, the ARMA(1,1) model coefficients are not significant, because the T-statistics are only -0.1634 and 1.5458. The second lag of the AR(2) model is not significant either (T-statistic -2.5593). The coefficient of the AR(1) model regressor, on the other hand, is significant (T-statistic is 4.6980). The smallest value of BIC (-4.5321) also supports the AR(1) model. The eventual model choice is therefore the first order autoregressive model.

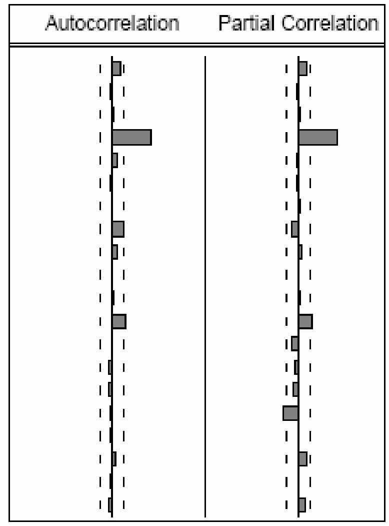
Table 10. *Model comparison: Bayes information criteria (BIC), R-squared, adjusted R-squared, variable coefficients and T-statistics.*

Model	BIC	R^2	Adj. R^2	Variable	Coefficient	T-statistic
AR(1)	-4.5321	0.0627	0.0588	C	0.0018	0.8645
				AR(1)	0.2494	4.6980
AR(2)	-4.5267	0.0785	0.0708	C	0.0020	0.9993
				AR(1)	0.2851	5.0960
				AR(2)	-0.1164	-2.5593
ARMA(1,1)	-4.5237	0.0758	0.0681	C	0.0018	0.9067
				AR(1)	-0.0358	-0.1634
				MA(1)	0.3196	1.5458

The R-squared of the AR(1) model is 0.0627 and the adjusted R-squared 0.0588. This means that only a marginal proportion, about 6.3%, of the price change is explained by historical price data. Thus, the price can be predicted only to a very small extent. According to Campbell et al. (1997, 80), financial asset returns are often predictable to some degree. Malkiel (2003, 62) emphasizes the difference between statistical and economical significance in findings of autocorrelation. In his opinion, the most important aspect of informational efficiency is that market participants cannot continuously make a revenue that is above average. If these momentums occur in financial markets, they are offset by transaction costs, or arbitraged away as soon as they become public. (Malkiel 2003, 62-63.)



Residuals



Squared residuals

Figure 14. *Correlograms of residuals and squared residuals.*

Table 11. *Correlograms and Ljung Box Q-statistics with p-values of residuals and squared residuals.*

Residuals					**Squared residuals**			
k	**AC**	**PAC**	***Q***	**p**	**AC**	**PAC**	***Q***	**p**
1	0.04	0.04	0.31	-	0.10	0.10	2.46	-
2	-0.11	-0.11	3.39	0.07	-0.01	-0.02	2.50	0.114
3	-0.01	0.00	3.41	0.18	0.03	0.03	2.69	0.261
4	0.15	0.14	8.72	0.03	0.43	0.43	48.26	0
5	-0.07	-0.08	9.93	0.04	0.07	-0.01	49.60	0
6	0.04	0.08	10.26	0.07	-0.02	-0.01	49.68	0
7	0.04	0.02	10.64	0.10	0.02	0.02	49.74	0
8	-0.10	-0.12	13.17	0.07	0.13	-0.07	54.12	0
9	-0.03	0.02	13.37	0.10	0.06	0.04	55.12	0
10	0.08	0.05	15.18	0.09	0.00	0.01	55.12	0
11	0.04	0.02	15.54	0.11	0.03	0.02	55.33	0
12	-0.16	-0.13	22.33	0.02	0.16	0.15	61.73	0
13	-0.06	-0.05	23.18	0.03	0.01	-0.07	61.74	0
14	-0.02	-0.06	23.30	0.04	-0.03	-0.04	61.99	0
15	0.00	-0.01	23.30	0.06	-0.04	-0.06	62.32	0
16	-0.09	-0.07	25.26	0.05	-0.02	-0.18	62.46	0

The accuracy of the model is assessed by examining the autocorrelation (AC) and partial autocorrelation (PAC) coefficients of residuals and squared residuals. If the residuals and squared residuals are autocorrelated, the model does not take account of all predictable factors. The AC and PAC coefficients are presented in Figure 14, with 95% probability bounds, and numerically along with the Ljung-Box *Q*-statistic and its p-value in Table 11. The AC and PAC coefficients of residuals are insignificant at a 5% significance level. The null hypothesis of no autocorrelation cannot be rejected with certainty, for the p-values of the Ljung-Box *Q*-statistic are only 0.03-0.18. The squared residuals, however, contain strong serial correlation at the fourth lag. At the fourth lag, the p-value drops to zero.

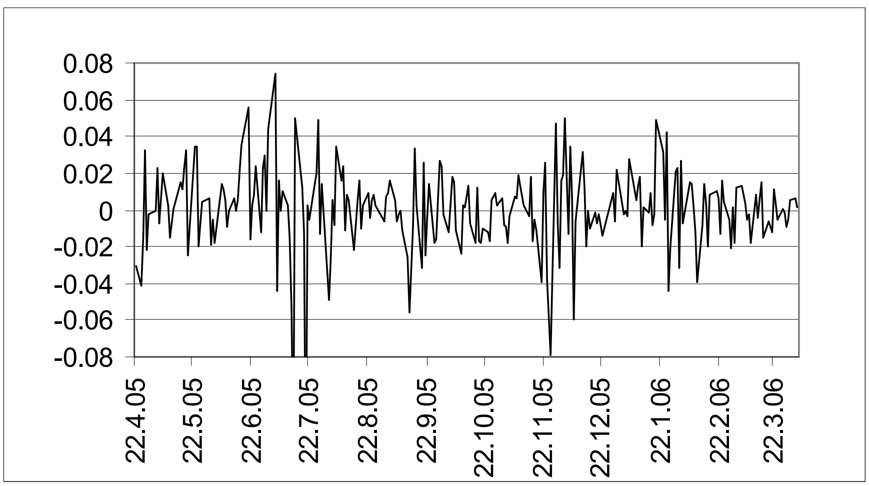


Figure 15. *Residuals of AR(1) model of differentiated logarithmic EUA series.*

The autocorrelation of residuals and squared residuals refers to time-varying heteroskedasticity, in other words, volatility clustering. Figure 15 presents the residuals of the AR(1) model. The figure shows that at times the absolute forecast errors of the model are less than two percent units, but at times they are way above. The residuals express time-varying heteroskedasticity. The volatility clustering could be modelled by adding an autoregressive conditional heteroskedasticity (ARCH) or generalized ARCH (GARCH) part to the autoregressive model. In the ARCH model, the error term's variance depends on its past squared values. In the GARCH model, the variance depends also on its own lagged values. (Stock & Watson 2003, 562-563.)

6 Conclusions

The aim of this thesis was to examine the European Union emission allowance markets from an informational efficiency point of view. The issues in focus were if the market price reflects all relevant information and if it reacts fast to new information. In an informationally efficient market, future prices are unpredictable, although price formation principles are known to all market participants. The unpredictability is due to randomly arriving new information. In consequence, it is impossible for anyone to make continuously above average profits in the market. The informational efficiency theory is tested with econometric analyses. The analyses rely on the weak informational efficiency hypothesis, which requires that prices reflect all information contained in historical prices. The econometric conditions are defined by a general random walk hypothesis RW3.

The results of the random walk analysis, the autocorrelation coefficients and the variance ratio test, show that the EUA price series does not fulfil the requirements of a random walk. The variance increases linearly, but there is serial correlation present in the time series. However, from the perspective of informational efficiency, the random walk criterion might not be necessary. To prove that the EUA markets are efficient, it suffices that the price development is unpredictable. The best possible autoregressive model has an R-squared of 6.3%. The econometric conclusion of the results is that there is significant autocorrelation present and the markets are not informationally efficient. However, in practice it seems impossible to make economic profit of historical price data. It is important to distinguish this economic aspect from the econometric one. The results are similar to other financial market analyses. Financial asset returns are often predictable to some extent, but predictability can rarely be used to constantly beat the market. At least, the momentums disappear in the long run. Transaction costs may be a reason why all arbitrage opportunities are not taken advantage of. (Campbell et al. 1997, 80; Malkiel 2003, 61-62). The conclusion is that the EUA market may still be efficient in spite of the predictability.

The predictability analysis could be extended by adding the possibility of volatility clustering to the autoregressive model. The 30-day rolling volatility presented in Figure in chapter 4.1 as well as the residuals reported in Figure 15 in chapter 5.3 suggest that volatility clustering is present. An autoregressive conditional heteroskedasticity (ARCH) model or generalized ARCH model would produce more accurate results.

The analysis was carried out with daily closing prices. It is possible that weakly data would be a better choice. The daily prices may be affected by factors that increase heteroskedasticity. It is also possible that many market participants change their position more seldom than would be reasonable due to trading costs. For these reasons weakly data is worth examining, as well as monthly data when enough observations are available. According to initial econometric study, weakly EUA data contains less autocorrelation than the daily data.

It could be fruitful to analyze informational efficiency of the EUA market also with event studies or tests for private information. With event studies, it would be possible to examine price reactions to the announcement of new information and draw conclusions about the rapidity of the reactions and market participants' understanding of price formation. Tests for private information would reveal if some market participants that have access to special information can make extra profits in the long run.

As time goes by and the EUA markets mature, informational efficiency is bound to develop further. The markets will see more participants, larger volumes, and better understanding of emissions trading and the ETS. The strengthening of the political framework and regulation would advance efficiency by decreasing uncertainty and clarifying the principals of price formation.

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Appendix

I. Volatility

Volatility is attained by calculating the standard deviation of logarithmic price returns, $r_t = \ln\left(\frac{P_t}{P_{t-1}}\right)$ and multiplying the standard deviation by the correct factor, which in the case of stock prices traded five days a week is $\sqrt{250}$. This is expressed as a single equation:

$$volatility = \sqrt{\frac{250}{n-1}\sum_{t=1}^{n}\left(r_t - \bar{r}\right)^2}\ , \qquad [A1]$$

where n is the number of observations, r_t the logarithmic price return and $\bar{r}$ the mean of logarithmic price returns. (Clewlow & Strickland 2000, 40; Hull 2000, 242.)

II. Akaike and Bayes information criteria

The right number of lags in a unit root test or an autoregressive model can be estimated by minimizing the Akaike or Bayes information criteria. The Akaike is prefferred in the case of unit root tests, the Bayes in the case of an autoregressive model. The Akaike information criteria (AIC) is the following:

$$AIC(p) = \ln\left(\frac{\sum_{t=1}^{n}\hat{\varepsilon}_t^2}{T}\right) + (p+1)\frac{2}{n}, \qquad [A2]$$

where p is the number of lags, $\hat{\varepsilon}_t$ are the ordinary least squares residuals, and n the number of observations. The Bayes information criteria is very similar:

$$BIC(p) = \ln\left(\frac{\sum_{t=1}^{n}\hat{\varepsilon}_t^2}{T}\right) + (p+1)\frac{\ln T}{n} \qquad \text{[A3]}$$

(Stock & Watson 2003, 453-455, 487.)

III. Ljung Box *Q*-statistic

The Ljung Box *Q*-statistic at lag k is calculated by:

$$Q = n(n+2)\sum_{j=1}^{k}\frac{\rho_j^2}{n-j}, \qquad \text{[A4]}$$

where n is the number of observations, and ρ_j^2 the jth autocorrelation coefficient. The Q-statistic is distributed as a chi-squared with degrees of freedom equal to the number of autocorrelations. (EViews 5 user's guide quide 2004, 316.)

IV. Variance ratio test

The standardized test statistic, $\psi(q)$, for null hypothesis RW3, in the presence of heteroskedasticity is:

$$\psi(q) = \frac{\sqrt{nq}\left(\overline{VR}\right)(q) - 1)}{\sqrt{\hat{\theta}}} \sim \mathrm{N}(0,1), \qquad \text{[A5]}$$

where nq denotes the number of observations, $\hat{\theta}$ is a heteroskedasticity-consistent estimator of $\theta(q)$, the asymptotic variance of $\overline{VR}(q)$:

$$\hat{\theta}(q) = 4\sum_{k=1}^{q-1}\left(1-\frac{k}{q}\right)^2 \hat{\delta}_k \, , \tag{A6}$$

where $\hat{\delta}_k$, on the other hand, is a heteroskedasticity-consistent estimator of δ_k, the asymptotic variance of $\hat{\rho}(k)$:

$$\hat{\delta}_k = \frac{nq\sum_{j=k+1}^{nq}(p_j - p_{j-1} - \overline{\mu})^2 (p_{j-k} - p_{j-k-1} - \overline{\mu})^2}{\left[\sum_{J=1}^{nq}(p_j - p_{j-1} - \overline{\mu})^2\right]^2} \, . \tag{A7}$$

(Campbell et al. 1997, 49-55.)